NPS-97-06-003

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SHIP ANTI BALLISTIC MISSILE RESPONSE (SABR)

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June 2006

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Prepared for: Deputy Chief of Naval Operations for Warfare
Requirements and Programs (OPNAV N7), 2000 Navy
Pentagon, Rm. 4E392, Washington, D.C. 20350-2000

REPORT DOCUMENTATION PAGE *Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** June 2006	**3. REPORT TYPE AND DATES COVERED** Thesis Technical Report

4. TITLE AND SUBTITLE Ship Anti Ballistic Missile Response (SABR)

5. FUNDING NUMBERS

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8. PERFORMING ORGANIZATION REPORT NUMBER NPS-97-06-003

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Deputy Chief of Naval Operations for Warfare Requirements and Programs
(OPNAV N7), 2000 Navy Pentagon, Rm. 4E392, Washington, D.C. 20350-2000

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE
A

13. ABSTRACT *(maximum 200 words)*

Based on public law and Presidential mandate, ballistic missile defense development is a front-burner issue for homeland defense and the defense of U.S. and coalition forces abroad. Spearheaded by the Missile Defense Agency, an integrated ballistic missile defense system was initiated to create a layered defense composed of land-, air-, sea-, and space-based assets. The Ship Anti-Ballistic Response (SABR) Project is a systems engineering approach that suggests a conceptualized system solution to meet the needs of the sea portion of ballistic missile defense in the 2025-2030 timeframe. The system is a unique solution to the sea-based ballistic missile defense issue, combining the use of a railgun interceptor and a conformable aperture skin-of-the-ship radar system.

4. SUBJECT TERMS Ballistic Missile Defense (BMD), Collaborative Information Exchange (CIX), Automated Battle Management System (ABMS), Network Centric Warfare (NCW), Ship Anti-Ballistic Response (SABR), Systems Engineering (SE)

15. NUMBER OF PAGES
334

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UL

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ABSTRACT

Based on public law and Presidential mandate, ballistic missile defense development is a front-burner issue for homeland defense and the defense of U.S. and coalition forces abroad. Spearheaded by the Missile Defense Agency, an integrated ballistic missile defense system was initiated to create a layered defense composed of land-, air-, sea-, and space-based assets. The Ship Anti-Ballistic Response (SABR) Project is a systems engineering approach that suggests a conceptualized system solution to meet the needs of the sea portion of ballistic missile defense in the 2025-2030 timeframe. The system is a unique solution to the sea-based ballistic missile defense issue, combining the use of a railgun interceptor[1] and a conformable aperture skin-of-the-ship radar system.

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[1] *Faculty Advisor's Note:* There are four major technical challenge areas associated with the transition of the railgun to the fleet. These are Barrel/Rail Life, Pulsed Power Management, Ship Integration, and Projectile Material and Guidance. Barrel/Rail Life addresses the issues associated with developing a material lining system which can withstand the repeated multiple launches required by the BMD mission. Pulsed Power Management encompasses the shipboard system required to store and deliver the significant amounts of pulsed power required for firing of the railgun. Ship Integration issues include all of the ship design requirements associated with the railgun including EMI/EMP effects and heat rejection. Projectile Material and Guidance addresses the significant challenges associated with Atmospheric heating and projectile guidance. Creating a railgun with the specific parameters in this report is not currently feasible given current technologies associated with the four major technical challenge areas, especially as they relate to system requirements for the firing rates, guidance, and top end projectile accelerations and velocities used in this study. Although the project parametric results examine alternate capabilities needed to meet the future threat, the study does not address the technological aspects of creating a physically feasible railgun to achieve the top end performance that would be needed to meet the worst case scenarios used in the study. Those aspects are addressed in more detail in a follow on study in the NPS Total Ship Systems Engineering (TSSE) program to be completed in December 2006. If these technological challenges are met in future developments, then the railgun implementation analysis used in this study can be used as part of the solution to the ballistic missile threat.

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

A

AAM: Air-to-Air Missile

AAW: Anti-Air Warfare

ABMS: Automated Battle Management System

ANOVA: Analysis of Variance

AOA: Angle of Attack

AOR: Area of Responsibility

APS: American Physical Society

AREPS: Advanced Refractive Effects Prediction System

ASW: Anti-Submarine Warfare

AT/FP: Anti-Terrorism/Force Protection

B

BDA: Battle Damage Assessment

BM: Ballistic Missile

BMD: Ballistic Missile Defense

C

C2: Command and Control

CA: Certification Authority

CAC: Common Access Card

CAIV: Cost as an Independent Variable

CC: Common Criteria

Cd: Drag Coefficient

CF2: Conformable (radar) Version 2

CG: Center of Gravity

CIWS: Close In Weapon System

CIX: Collaborative Information Exchange

Cl: Lift Coefficient

COIL: Chemical Oxygen Iodine Laser

COMPSEC: Computer Security

COMSEC: Communications Security
CONOPS: Concept of Operations
COP: Common Operational Picture
CSG: Carrier Strike Group

D

DAA: Designated Approving Authority
DAC: Discretionary Access Control
DEW: Directed Energy Weapon
DHS: Department of Homeland Security
DII: Defense Information Infrastructure
DISA: Defense Information Systems Agency
DITSCAP: DoD Information Technology Security Certification and Accreditation Process
DoD: Department of Defense
DRM: Design Reference Mission
DRMP: Design Reference Mission Profile

E

EM: Electromagnetic
EMI: Electromagnetic Interference
EMP: Electro Magnetic Pulse
EMSEC: Emissions Security
EO: Electro-Optic
ESG: Expeditionary Strike Group

F

FC: Fire Control
Fd: Drag Force
FEL: Free Electron Laser
FFBD: Function Flow Block Diagram
FIFO: First In First Out

G

GCCS: Global Command and Control System

GPS: Global Positioning System

GUI: Graphical User Interface

H

HM&E: Hull, Mechanical, and Electrical

HOQ: House of Quality

I

IA: Information Assurance

IBMD: Integrated Ballistic Missile Defense

ICBM: Intercontinental Ballistic Missile

ID: Identification

INFOSEC: Information Systems Security

INS: Inertial Navigation System

IR: Intermediate Range

IS: Information System

IT: Information Technology

J

JBFSA: Joint Blue Force Situational Awareness

JCRE: Joint Coordinated Real-Time Engagement

L

Lf: Lift Force

LFS: Load Factor Sensibility

M

MAC: Mandatory Access Control

MCO: Major Combat Operations

MDA: Missile Defense Agency

MFPAR: Multifunction Phased Array Radar

MOE: Measure of Effectiveness

MOP: Measure of Performance

MR: Medium Range

MYSEA: Monterey Security Architecture

N

NASA: National Aeronautics and Space Administration

NATO: North Atlantic Treaty Organization

NCDC: National Climatic Data Center

NOAA: National Oceanic and Atmospheric Administration

NPS: Naval Postgraduate School

P

PASR: Phased Array Surveillance Radar

Pd: Probability of Detection

Pe: Probability of Engagement

Pfa: Probability of False Alarm

Pk: Probability of Kill

PRC: People’s Republic of China

PSI: Personnel Security Investigation

Q

QFD: Quality Function Deployment

R

RAID: Redundant Arrays of Independent Disks

RF: Risk Factor

RG: Railgun

RHIB: Rigid Hull Inflatable Boat

S

SABR: Ship Anti-Ballistic missile Response

SAM: Surface-to-Air Missile

SDI: Strategic Defense Initiative

SE: Systems Engineering

SEA: Systems Engineering Analysis

SNR: Signal-to-Noise Ratio

SOTSR: Skin-of-the-Ship Radar

SPAWAR: Space and Naval Warfare Systems Command

SR: Short Range

SR to IR BM: Short Range, Medium Range, and Intermediate Range Ballistic Missile

SR to IR BMD: Short Range, Medium Range, and Intermediate Range Ballistic Missile Defense

SSAA: System Security Authorization Agreement

SSBN: Nuclear-powered Ballistic Missile Submarine

SSKP: Single Shot Kill Probability

STAMP: Strategic and Theater Attack Modeling Process

T

TBM: Theater Ballistic Missile

TBMD: Theater Ballistic Missile Defense

TCX: Trusted Computing Exemplar

TDSI: Temasek Defence Systems Institute

ToF: Time of Flight

TPM: Technical Performance Measure

TSSE: Total Ship Systems Engineering

T/R: Transmit/Receive

TRL: Technology Readiness Level

U

UN: United Nations

UNREP: Underway Replenishment

U.S.: United States

USD: U.S. Dollars

USN: United States Navy

USSR: Union of Soviet Socialist Republics

V

VLA: Vertically Launched ASROC

VLS: Vertical Launching System

VOD: Vertical On-board Delivery

W

WMD: Weapon of Mass Destruction

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It is the policy of the United States to deploy as soon as is technologically possible an effective National Missile Defense system capable of defending the territory of the United States against limited ballistic missile attack (whether accidental, unauthorized, or deliberate) with funding subject to the annual authorization of appropriations and the annual appropriation of funds for National Missile Defense.

– National Missile Defense Act of 1999 (Public Law 106-38)

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PREFACE

Sea-based Ballistic Missile Defense (BMD) is developing into a new front-line shipboard warfare area, along the same lines and importance as anti-submarine warfare and anti-air warfare. A significant developmental effort is being applied by various agencies within the U.S. Department of Defense (DoD) to mature the technologies associated with this mission.

This project seeks to look at current technologies which are in the developmental and the conceptual stages, and to use a systems engineering process to determine a conceptual system architecture to fulfill the sea-based BMD mission 20-25 years from now, 2025-2030. This project looks at the entire "kill chain," from initial detection of the launch of a ballistic missile through the tracking, identification, and interception phases, and to post-engagement assessment. The intent of this study is to provide the reader a comprehensive analysis of the mission problem, a well-researched examination of various physically feasible system alternatives, and offer a recommendation for a suggested path for future development.

* * *

The challenge of large scale, complex problem solving is often determining the actual nature of the problem. To accomplish this, one must understand the context, complexities, deficiencies, and timeline of the problem in order to start down the path towards a solution.

Oftentimes problems are very broad in nature and require definition prior to creating a plan of action. Such is the case of sea-based ballistic missile defense study. The original tasking, "Use a top-down, system of systems approach to examine future surface combatant operations in terms of their conduct and support of current and emerging sea-based Theater Ballistic Missile Defense (TBMD) missions,"[2] covered a wide landscape of possibilities. Though the preceding statement offered direction and a basic topic in which to conduct the study, it does not explain what the actual problem(s)

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[2] Wayne E. Meyer Institute of Systems Engineering, "SEA-9 Integrated Projects Objectives," (Unpublished Memorandum: 2005).

that required solving. Based on group interpretation of the tasking statement, consultation with external resources in the DoD and industry, and historical knowledge of both surface combatant systems and BMD systems, it was determined that the problems are:

- There is no operational sea-based BMD capability
- There is no integrated network to connect all players in BMD (sea, air, land, and space) for layered defense
- Current systems in development will not be able to compete with future developments in ballistic missile technology
- Current systems in development will not be able to counter large salvos of ballistic missiles

With such a range of possibilities, ideas conceived within the group for project direction were widespread. The initial brainstorming sessions eventually developed into a classic detect-to-engage scenario as the base functionality for the system to be developed. Figure Preface-1 is the result from the brainstorming sessions depicting critical aspects of a BMD system and the perceived subcomponents that encompass the system as a whole.

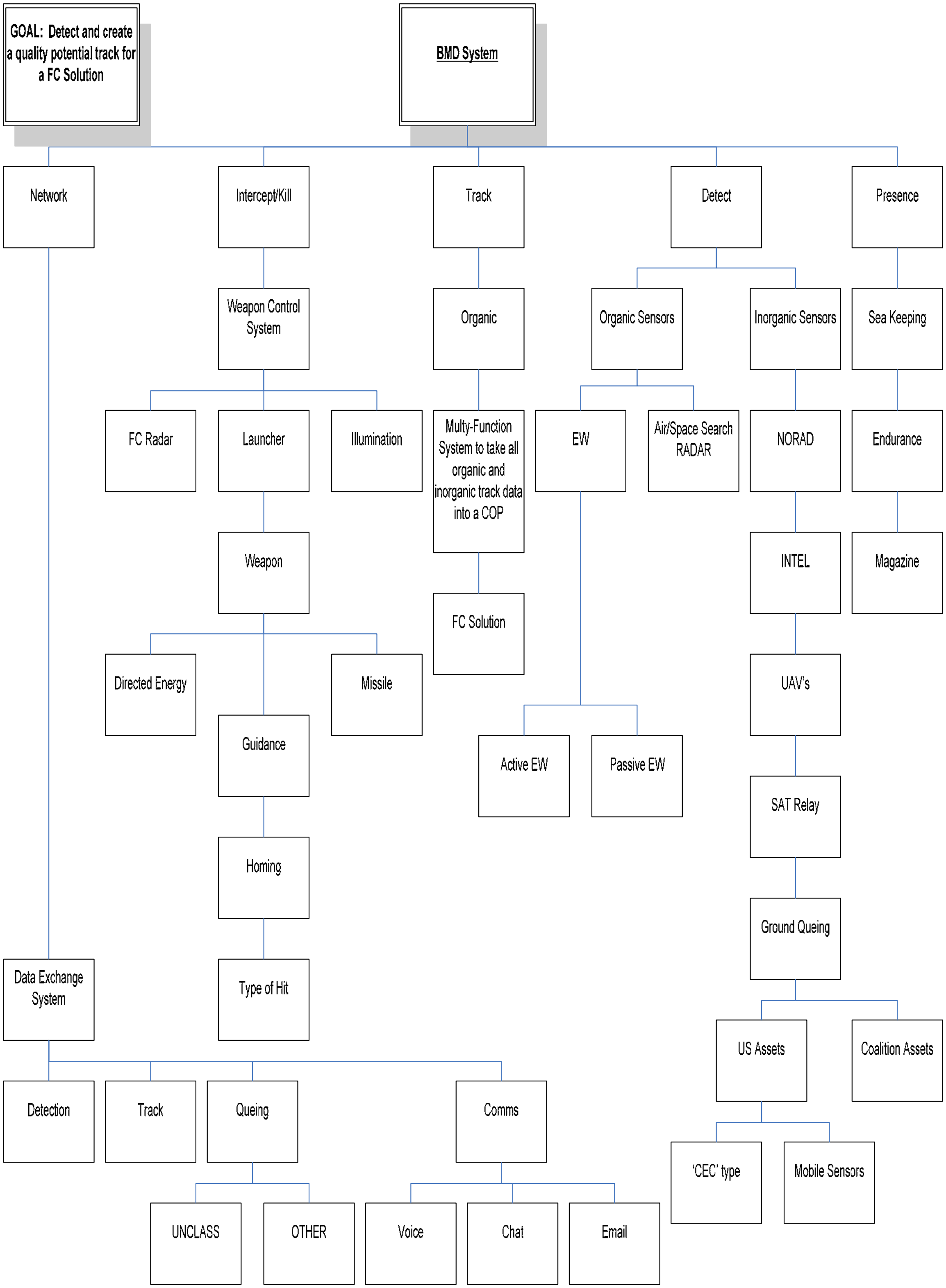

Figure Preface-1. Initial BMD System Ideas

Brainstorming efforts often reveal a large scope of topics that must be addressed in order to develop a solution. The core issues for the conceptual system (solution for the problems) that were revealed from these sessions were:

- Current and Prospective Threats (principle measure for performance evaluation)
- Network (data and voice exchange)
- Sensors
- Seaframe
- Interceptor
- Command and Control (C2)

CURRENT AND PROSPECTIVE THREATS

This issue addresses the current threats and prospective threat attributes that are applicable in the timeframe of the study (2025-2030). Key attributes include:

- size (mass, dimensions, etc.)
- fuel type
- number of stages
- mobile or fixed launch (or both)
- proliferation
- number of warheads
- decoy capability
- range
- expected velocities throughout trajectory
- radar cross section
- max altitude (range dependent)

NETWORK

The network is the means to communicate and exchange data between all participating units in ballistic missile defense. Key attributes of the network include:

- number of required data feeds
- cryptological requirements (security)

- expected size (bytes) of significant BMD information (bandwidth consideration)
- interoperability with participating BMD units
- ability to exchange detection, tracking and fire control (FC) data

SENSOR

Sensors and their networking is a critical issue for ballistic missile defense. If launches and ballistic missiles in flight are not detected, then interception is impossible. This issue considers the attributes required for the whole of BMD (on and off the ship) Key attributes for sensors include:

- capability to detect ballistic missile launches and missiles in flight from space
- number of required satellites to provide continuous worldwide BMD coverage
- capability to detect ballistic missile launches and missiles in flight from land-based sensors
- number of required land based sensors to provide BMD coverage in key world “hotspots”
- sea-based capability to detect ballistic missile launches and ballistic missiles in flight
    - ➢ sensor sensitivity
    - ➢ sensor power requirements
    - ➢ sensor rate of track/update
    - ➢ sensor error
    - ➢ sensor maximum and effective ranges
    - ➢ sensor altitude
    - ➢ sensor interoperability with nonorganic detection system
    - ➢ sensor compatibility with ship display, weapon control, and C2 system

SEAFRAME

In order for the preceding components to participate in the integrated BMD of a given region, there must be a means of getting the components on station. Since the tasking directive specified “sea-based” BMD, the logical response was a ship or seaframe. The term seaframe is generic term used to describe a nondescript, yet nonfixed, sea-based vessel capable of mobility, sustainability, and reliability to conduct the given mission at hand (regional BMD). Specific characteristics of the seaframe include:

- capability to arrive on station at a given time (speed)
- capability to maintain station for a given period of time (endurance)
- capability to provide requisite power for all BMD systems
- capability to provide favorable conditions for BMD system component operation (stability)
- capability to contain requisite BMD system components (capacity)

INTERCEPTOR

The means for completing a ballistic missile defense engagement is the interceptor. The interceptor encompasses three key aspects necessary to putting ordinance on target: the launcher, the projectile, and projectile guidance. The key attributes of the interceptor for this study include:

- type (e.g., missile, directed energy weapon (DEW), railgun, etc.)
- depth of magazine
- rate of fire (accounts for reliability)
- power requirements
- launcher configuration (e.g., vertical, slewed-turret, etc.)
- compatibility with ship weapon control and C2 system
- launcher size (includes mass, dimensions, etc.)
- interceptor size (if applicable; includes mass, dimensions, etc.)
- interceptor speed
- interceptor maximum and effective ranges
- interceptor ability to receive guidance
- interceptor maneuverability
- interceptor kill mechanism (warhead, KKV, energy duration, etc.)

COMMAND AND CONTROL (C2)

The final critical element of BMD is decision making. Whether controlled by computer or an actual commander, C2 decisions are essential to an effective defense. The requisite attributes for C2 are:

- Common Operation Picture (COP) for BMD (covering BMD asset positions and threat activity)
- Interceptor inventory of all available
- Network and communication availability

The next logical step in development of the study's plan of attack would be to solicit input from customers to determine the actual overall needs and desires for the system's performance. This aspect of system development did not occur in this study. No customers or stakeholders initiated this study; rather the Wayne E. Meyer Institute for Systems Engineering produced the tasking directive (mentioned previously) and let the student team develop the problem statement, needs, and scope of the study under the auspices of faculty advisors and Institute approval.

Scope

Unhindered by external customer guidelines, the broad scope of the sea-based ballistic missile was intentionally narrowed. This was due to both the complexity of the sea-based BMD issues and a very brief timeframe (just under five months from tasking to conceptual system design). As any one of the previously mentioned core areas brainstormed for BMD could constitute systems sufficiently complex for a systems engineering integrated study, the scope was confined to two areas of BMD (commit stage and intercept stage) and anchored with the seaframe as the "hub" of the system. As such, the only variables to be explored, altered, and forecasted would those aspects that are seaframe-oriented. These aspects would be referred to as organic aspects. Those aspects that are external to the seaframe or nonorganic aspects, would be fixed entities that would be binary in nature (their attributes are part of the system or not) in order to demonstrate the system capability of both organic and non-organic together or just the performance of the organic system alone.

The two core areas of this BMD study, commit and intercept, are the governing factors of system development. Every aspect explored in the study falls under one of these areas. These areas are defined as:

- **Commit** – All actions taken to detect, track, identify, develop a fire control solution, and make a C2 decision to intercept a ballistic missile.
- **Intercept** – All actions that occur from the decision to employ an interceptor until a ballistic missile is destroyed, handed off, or reaches the end of its midcourse phase.

Any aspects of BMD that precede or occur after these areas were the first items to be designated outside the scope of the study.

Rooted in the original tasking statement and later in the problem statement, the team developed a list of sea-based BMD aspects that are a part of the study's scope and those that are outside the scope due to relevance, complexity (time issue), and by definition of sea-based BMD.[3] The following are aspects that were considered as "in-scope" this study:

- [The system is] Part of the overall layered U.S. Integrated Ballistic Missile Defense System (IBMDS) and coalition BMD effort (the sea-based portion of BMD)
- 2025-2030 timeframe[4]
- Sea-based
- Must counter the perceived SR to IR ballistic missile threats[5]
- Intercept warhead in the boost through midcourse phases[6] (earliest engagement possible)

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[3] By direction of the Missile Defense Agency (MDA), sea-based BMD is confined to boost through midcourse intercept of short-range to intermediate-range ballistic missiles (500 km - 3,500 km). Missile Defense Agency, "MDA Link," http//www.mda.mil/mdalink, (Washington, D.C.: 2006).

[4] Deliberate decision by the group to meet the "future surface combatant operations for emerging sea-based BMD" portion of the tasking statement beyond the projected developmental timeline of DD-X and CG-X.

[5] "Perceived" refers not necessarily to the most dangerous threat of the future, but the likely, highly-proliferated ballistic missile easily bought and sold by nations, factions, and terrorists alike. Missile Defense Agency, "MDA Link," http//www.mda.mil/mdalink, (Washington, D.C.: 2006).

[6] Ibid.

The following are those items deemed "out-of-scope" based on the reasons mentioned previously, faculty and external advisor assistance, and team preference:

- BMs that survive beyond midcourse will not be engaged by the sea-based system[7]
- Post-intercept debris collateral damage and intercept over-flight issues
- Vulnerability of the ship due employment of sensors, FC radar, and employment of interceptor(s) (EW signature)
- Ability for ship self-defense while conducting active BMD (will be covered by ship self-defense system)
- Nonphysical interceptors (cyber attack, etc.)

Assumptions

Determining the project scope is just one part in the definition of the study. To focus on a select few elements to generate a conceptual system design using systems engineering processes, many assumptions must be made. Since the focus of the study is sea-based BMD in a future timeframe (2025-2030), a certain level of expected capability must be assumed. Additionally, those external aspects (nonorganic aspects) that interact, support, and aid the organic system aspects must also have assumed capability that can be fixed in a variable sense. Based on this logic, the system-bounding assumptions are:

- Integrated external sensor network is deployed and operational for all Unified Commands[8]
- Collaborative Information Exchange (CIX) exists between all participants in the IBMDS
- BMD system will be installed as part of a ship[9]
- Physical interceptor(s) (i.e., missile, railgun, DEW, etc.) will be employed if able

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[7] This situation is treated as a "handoff" to which a terminal intercept system within the IBMDS would address.

[8] This indicates that there is worldwide sensor coverage available.

[9] This is to indicate that a "BMD barge" or fixed "BMD platform" off shore does not constitute sea-based BMD in the system to be developed.

- Automated Battle Management System exists on ship and interacts with other participants in regional BMD via CIX

The scope and system bounding assumptions define the breadth of the study and serve as enablers to ensure the quality of the study and that study is completed as per academic schedule constraints.

ACKNOWLEDGEMENTS

The SABR team acknowledges the contributions and assistance of the following individuals in the completion of this project:

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1.0 INTRODUCTION

1.1 BACKGROUND

This section presents the guidance provided to the Systems Engineering Analysis Cohort Nine (SEA-9) Future Surface Combatant Ballistic Missile Defense Integrated Project Team (SEA-9 BMD) received for this campus-wide integrated project and provides the underlying basis for this thesis technical report. This project assumed the name SABR, for Ship Anti-Ballistic missile Response.

1.1.1 Project Motivation

The contemporary and emerging missile threat from hostile states is fundamentally different from that of the Cold War and requires a different approach to deterrence and new tools for defense. The strategic logic of containment and fear from mutually assured destruction that kept the United States, its allies, and the Soviet Union from all-out missile engagements does not exist in this new world order of irrational state, faction, or terrorist group leadership. These newer threats on the world stage see Weapons of Mass Destruction (WMDs) as weapons of choice, not weapons of last resort to exert political pressure or to evoke unpopular responses. In this case, ballistic missile (BM) WMDs are a lethal means to compensate for the conventional strength of the United States, allowing these entities to pursue their objectives through force, coercion, and intimidation.

To deter such threats, the United States and its allies must devalue BMs as tools of extortion and aggression through an overt regional presence and a formidable ballistic missile defense (BMD). Doing so would undermine the belief of adversaries that threatening a missile attack would succeed in affecting the secure status of the target citizenry and their way of life. In this way, although missile defenses are not a replacement for an offensive response capability, they are an added and critical dimension of contemporary deterrence.[10]

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[10] George W. Bush, "National Security Presidential Directive No. 23," (Washington, D.C.: The White House, 2002).

There are three critical factors that have changed in terms of BM development in comparison to the superpower model of the past.

- Newer BM and WMD development programs no longer follow the patterns initially set by the United States and the Soviet Union. These programs require neither high standards of missile accuracy, reliability and safety nor large numbers of missiles and therefore can be developed more rapidly.
- A nation that wants to develop BMs and WMDs can now obtain extensive technical assistance from outside sources. Foreign assistance is not a wild card. It is a fact.
- Nations are increasingly able to conceal important elements of their ballistic missile and associated WMD programs and are highly motivated to do so.[11]

From these three factors, it is crucial that the U.S. and its allies field a highly adaptable and rapidly deployable BMD capability to meet these emerging threats. Deterrence and defense against the BM threat must encompass the entire spectrum of threat capabilities to provide maximum security for the United States, U.S. forces, and allies.

1.1.2 Project Assignment

> Use a top-down, system of systems approach to examine future surface combatant operations in terms of their conduct and support of current and emerging sea-based Theater Ballistic Missile Defense (TBMD) missions.[12]

The intent of this thesis technical report is to look into the "future" of BMD in order to conceptualize a surface combatant-based system of systems that becomes part of the whole of integrated BMD as envisioned by the Department of Homeland Security (DHS), the Department of Defense (DoD), and the Missile Defense Agency (MDA).

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[11] Commission to Assess the Ballistic Missile Threat to the United States, "Executive Summary of the Report from the Commission to Assess the Ballistic Missile Threat to the United States," (Washington, D.C.: Congressional Record, 1998).

[12] Wayne E. Meyer Institute of Systems Engineering, "SEA-9 Integrated Projects Objectives," (Unpublished Memorandum: 2005).

BMD systems have been studied, conceptualized, and developed ever since the advent of BMs as a threat. As such, this study strives to be sensitive to the historical precedents of past and current systems, yet not constrained by their ideas (produced or conceptual in nature), in order to implement an objective approach to the development of a system of systems.

In the summer of 2005, it was announced that the SEA curriculum, for the first time, would have three integrated projects instead of one large integrated project. As a result, the Wayne E. Meyer Institute, the Temasek Defence System Institute (TDSI), and the students of the SEA-9 curriculum spent the summer and fall of 2005 determining ideas for project topics. Three broad topics emerged (Maritime Domain Awareness, Rapid Response Command and Control, and Future Surface Combatant Systems) and each student chose their topic that they wished pursue for their capstone project requirement. Each project was to be a campus-wide, integrated project focused on current issues facing the U.S. Navy and its coalition partners.

The topic of Future Surface Combatant Systems was a popular topic, attracting ten SEA students (just under half of the overall cohort); however, the topic was too broad for a focused integrated project. After examination of current operational obstacles, strategic visions of both the U.S. Navy and the United States as a whole, and emerging technologies of the near future, it was mutually decided by the Meyer Institute and students of the future surface combatant integrated project team (i.e., the SEA-9 BMD Integrated Project Team, prior to being renamed "SABR") to address the front-burner issue of ballistic missile defense, specifically the roles and requisite capabilities of a future surface combatant as a system in the whole of global BMD.

1.1.3 Project Definition

"Future surface combatant operations" is defined as looking 20-25 years into the future (2025-2030). This extends the scope beyond the 10-15 year development time frame of both DDG-1000 and CG-X, yet keeps the dates close enough to be synergistic with the development of limited-use current and future technologies such as conformable radars, railguns, and directed energy weapons (DEWs).

The "current and emerging sea-based TBMD missions" consideration for limited BMD capabilities currently employed in the Fleet and the overall concept of BMD must include the ability to detect and engage the threat as well as to exchange information between joint and coalition forces.

"Theater Ballistic Missile Defense (TBMD)" is defined as operating within an Area of Responsibility (AOR), meaning targets within a limited geographical area. This is interpreted as the deployment of the future surface combatant BMD system to a given region (theatre) to provide area defense. Further clarification for the role of sea-based BMD in the overall scheme of Integrated Ballistic Missile Defense (IBMD) assets is provided by the MDA, which designates "sea-based systems… to intercept short to medium range hostile missiles in the ascent and descent phase of midcourse flight"[13] and "capable of intercepting short and medium-range ballistic missiles."[14]

The result of this examination is the following Problem Statement:

> Develop and evaluate a conceptualized ship-based BMD system architecture to meet emerging short- to intermediate range ballistic missile threat capability in the 2025-2030 time frame. The system must be able to integrate with prospective coalition BMD architectures and contribute to the whole of layered BMD.

1.1.4 Ballistic Missile Defense (BMD) Definition

BMD is defined by the MDA as "the capability to defend forces and territories of the United States, its allies, and friends against all classes and ranges of ballistic missile threats."[15] Specifically, it categorizes the defense into the three phases of a BM trajectory: Boost, Midcourse, and Terminal, Figure 1.

Boost: The portion of flight immediately after launch, when the missile burns fuel (solid or liquid) to accelerate and lift its payload into the air. Duration is approximately 110-300 seconds.

Midcourse: The portion of flight where the missile payload is separated from the booster rocket and is traveling without power on its trajectory toward a target.

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[13] Missile Defense Agency, "MDA Link," http//www.mda.mil/mdalink, Washington, D.C.: 2006.

[14] Missile Defense Agency, *A Day in the Life of the BMDS*, 3rd Ed., Washington, D.C.: 2004, p. 17.

[15] Missile Defense Agency, "MDA Link," http//www.mda.mil/mdalink, Washington, D.C.: 2006.

Terminal: The final portion of flight when the missile's warhead reenters the earth's atmosphere (if exo-atmospheric) and falls toward its target, propelled only by its momentum and the force of gravity.

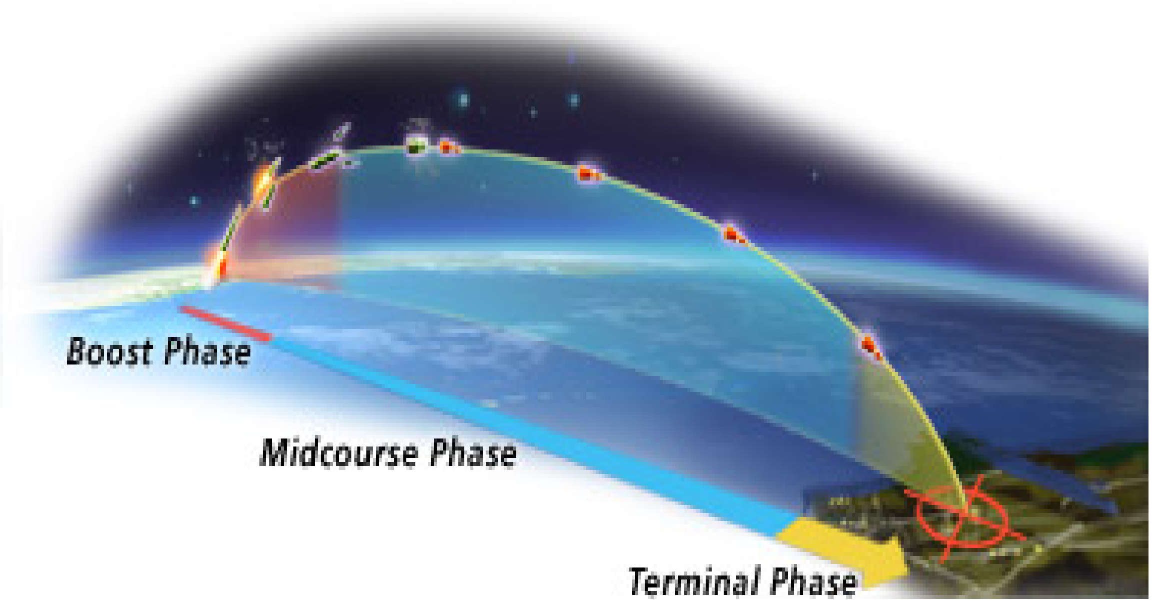

Figure 1. Trajectory Phases[16]

1.1.4.1 Theater Ballistic Missile Defense (TBMD) Definition

TBMD is the capability to defend forces, territories, and interests of the United States, its military allies, and friends against BM threats employed in a given geographical region. Specifically, it includes all classes of missiles that are employed against short-range (SR), medium-range (MR), and intermediate-range (IR) targets (500 km-3,500 km) within a given region.

Figure 2 depicts the different ranges and provides examples of each category of missile.

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[16] Raytheon Company, "Missile Trajectory Phases," http//www.raytheonmissiledefense.com/phases/index.html, Waltham: 2006.

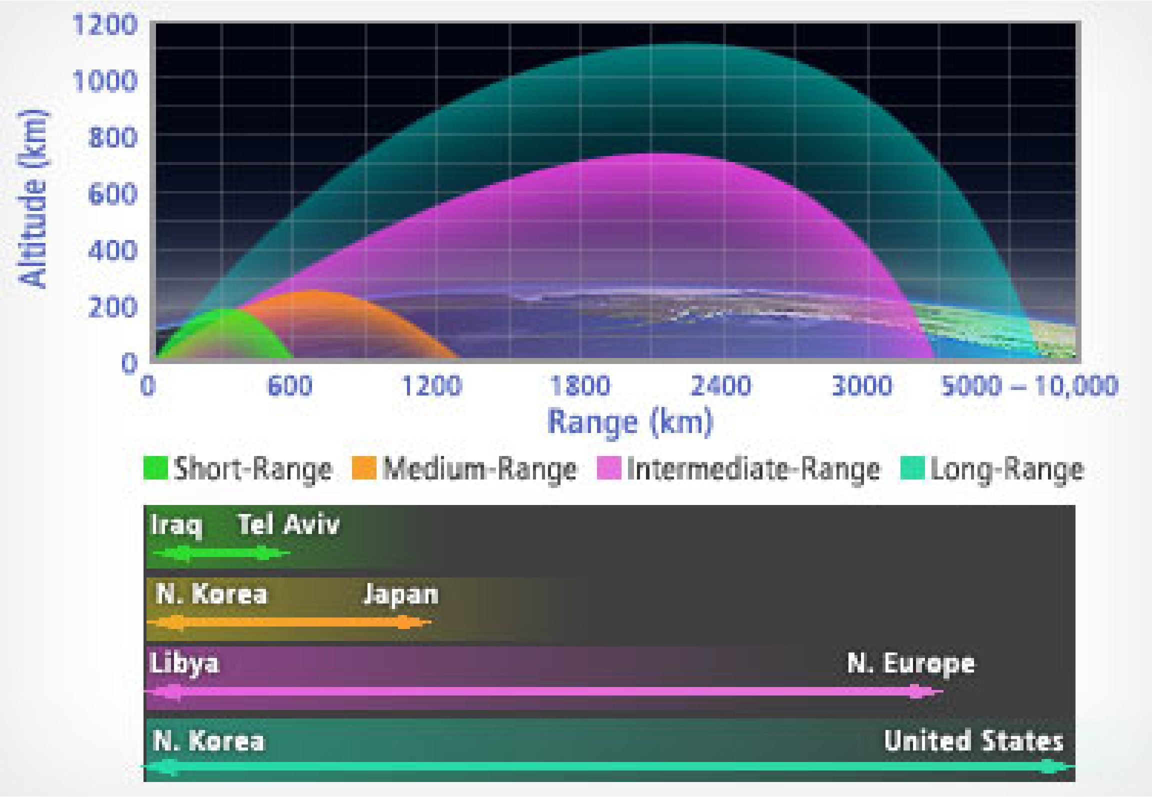

Figure 2. Missile Classifications by Range and Comparative Distances

2.0 OVERVIEW

2.1 SYSTEMS ENGINEERING (SE) PROCESS

The SE methodology is not a "one-size-fits-all" process. The definition and implementation of SE varies depending on the project environment and domain of application. Even though there are differences in definition, approach, and implementation, the SABR team developed and executed a viable SE process for this SABR project.

"A systems approach is one that focuses on the system as a whole, particularly when making valued judgments (what is required) and design decisions (what is feasible)."[17] The first priority is to realize that, "Inherent within the systems engineering process must be a provision for continuous feedback and corrective action."[18] SE is an iterative procedure that follows a top-down process (definition of the system), to a bottom-up approach (system validation), as seen in Figure 3. This is a continuous approach that is applied throughout the complete life cycle of the system, from system design to phase out and disposal.

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[17] M.W. Maier and E. Rechtin, *The Art of Systems Architecting*, 2nd Ed., CRC Press LLC, 2002, p. 8.

[18] B.S. Blanchard and W.J. Fabrycky, *Systems Engineering and Analysis*, 3rd Ed., Prentice Hall, Inc., 1998, p. 25.

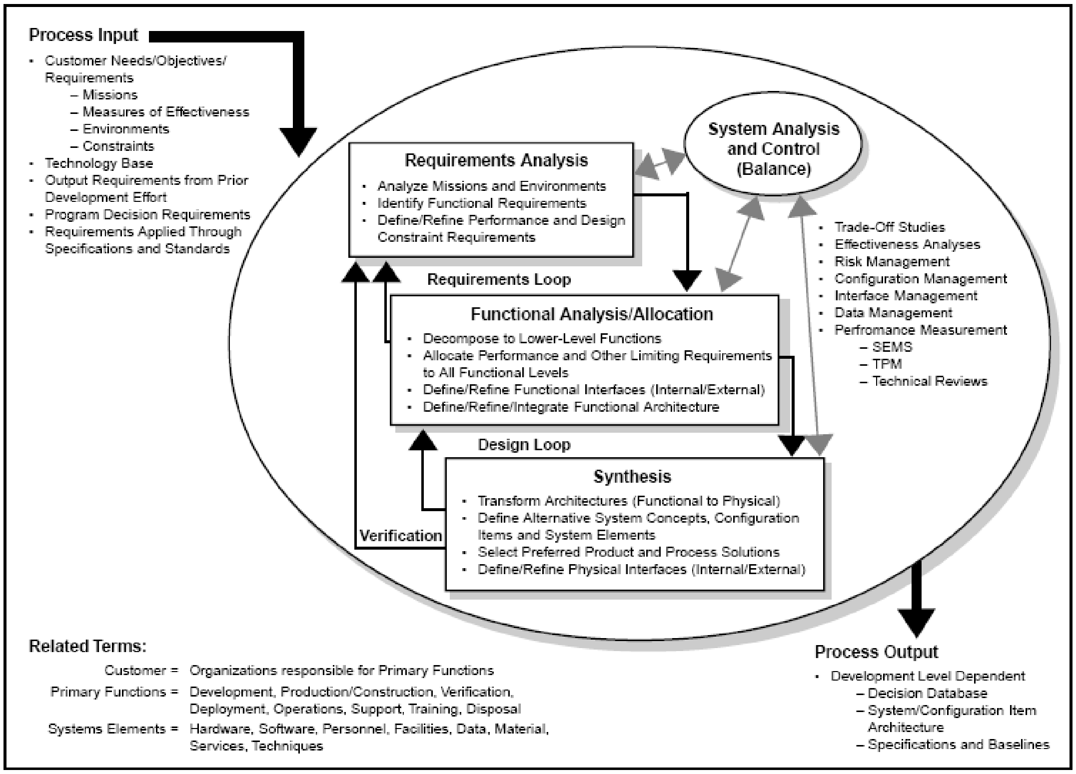

Figure 3. DoD Systems Engineering Process Model[19]

After validating the system needs and creating an operational concept definition from the customer, focus is placed on accurately defining and developing system neutral technical requirements. "Requirements definition is a core systems engineering process that begins with the considerations of what the stakeholder needs, and ends with the establishment of a requirements baseline for the project."[20] Not only is it important for the system requirements to be well defined, but they need to be traceable to the customer's needs and to the system and subsystems themselves to allow functional analysis and functional allocation to begin.

After defining the systems requirements, the SABR team can begin to develop Measures of Effectiveness (MOEs) and Measures of Performance (MOPs) to determine if the system meets requirements. After MOE and MOP definition, the functional analysis and allocation phase of the project allows for a functional architecture to be developed.

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[19] United States Department of Defense, Systems Management College, *Systems Engineering Fundamentals*, Defense Acquisition University Press, January 2001, p. 31.

[20] C. Whitcomb, Ph.D., "A Systems Engineering Process," Naval Postgraduate School, Monterey, CA, Winter 2006.

"Functional analysis is the iterative process of breaking down, or decomposing requirements from the system level, to the subsystem level, and as far down the hierarchal structure as necessary to identify specific resources and components of the system."[21] This will allow for development of solution neutral functions with regard to the customer's stated needs and technical requirements. The intent here is not to identify how the system will work, but identify what the system needs to do, and provide the first stable baseline of the system about which the SABR team can make reasonable judgments.

During the functional allocation process, similar functions are grouped together and the "whats" are converted into "hows" by mapping alternative components to functions. Functions can be accomplished by hardware, software, or peopleware. In this phase, different conceptual design architectures are developed and trade-off studies are conducted at many levels in order to identify the preferred design and proper combination of hardware, software, and peopleware. "From a systems engineering perspective, it is essential that the requirements for equipment, software, people, facilities, and so on, be justified by responding to some functional need."[22] By using tools such as Quality Function Diagrams (QFDs) and Function Flow Block Diagrams (FFBDs), a traceable method for developing design architecture is used. This allows for needs, requirements, MOEs, MOPs, and functions to be mapped together, justifying the architecture created.

As the system design alternatives start to come together, trade-offs progress. Trade-offs on technologies and components may continue into the synthesis, analysis, and evaluation phase of the project. It is important to note that feedback has been gathered from all phases of the SABR systems engineering process and subsequent changes have been made, as necessary.

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[21] B.S. Blanchard and W.J. Fabrycky, *Systems Engineering and Analysis*, 3rd Ed., Prentice Hall, Inc., 1998, p. 62.

[22] Ibid.

2.2 SHIP ANTI-BALLISTIC MISSILE RESPONSE (SABR) PROJECT SE APPROACH

In the SABR project, the SE process consisted of a multinational team dynamic all utilizing an SE process model to develop a BMD system. In the rest of this section, details are provided on the team's organization and the SABR project process, which has been utilized to develop the preferred architecture.

2.2.1 Project Team Organization

"Success in system engineering derives from the realization that design activity requires a 'team' approach."[23] Teamwork and effective communication are crucial to having a successful project. Hence, using a team approach is the foundation of the SABR project. The SABR team consisted of students from SEA-9, TDSI, and Total Ship Systems Engineering (TSSE). The SABR project was assigned to SEA-9 in lieu of individual theses, with tasking to integrate TDSI and TSSE for assistance in various specialty areas. Formulation of the team began with the Meyer Institute assigning a team lead from SEA-9, based on rank, to the project. From there, individuals within SEA-9 were assigned as component leads for different areas of the BM project. A full breakdown of the initial team format can be seen in the organization chart in Figure 4.

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[23] B.S. Blanchard and W.J. Fabrycky, *Systems Engineering and Analysis*, 3rd Ed., Prentice Hall, Inc. 1998, p. 104.

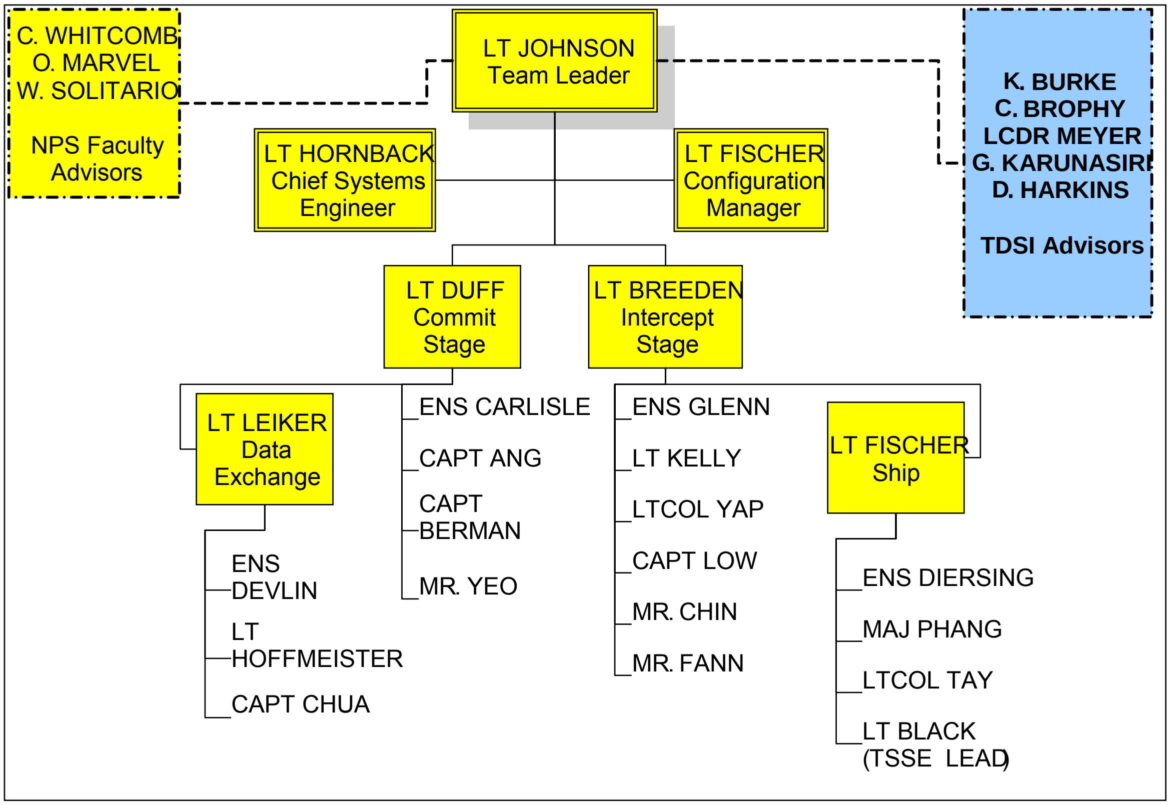

Figure 4. SABR Project Organization Chart

The students assisting from TDSI and TSSE brought a plethora of technical capabilities to the table. The TDSI students consist primarily of coalition military forces and various non-U.S. defense agencies. They brought technical experience in areas such as current and future radar capabilities and designs, as well as current and future missile and interceptor technologies. The TSSE students brought experience in the area of naval architecture. Outputs from the BMD project will be used by TSSE to develop a future platform capable of housing the BMD system.

2.2.2 Systems Engineering Process Model

With the team structure set, the systems approach was implemented. There are many different system process models and philosophies that can be used to represent the flow of the project work. In order to choose a process model the team had to investigate the characteristics of the project at hand. Certain process models work better for different situations. For example, the spiral process model is an iterative model based on a risk-driven approach. It spirals through each phase of development each time a prototype is developed, allowing for risk assessment before proceeding to the next phase, all the way to final system development.

Basically, all of the system process models end in some version of an operational system and utilize some method of feedback into the system to make corrections as needed to validate and verify. The end state of the SABR project and feedback into the system were major considerations, while determining what type of process model or philosophy to follow. In the case of the SABR project, there is no physical system development. The project goal is to develop and define a refined set of system requirements and a preferred system design concept, with sensitivity analysis that could be used to develop a future SABR system. The decision was made to follow the waterfall process model seen in Figure 5 as represented in Blanchard and Fabrycky's *Systems Engineering and Analysis*, because the SABR team chose to display the project approach as a progression from phase to phase, allowing for feedback when necessary.

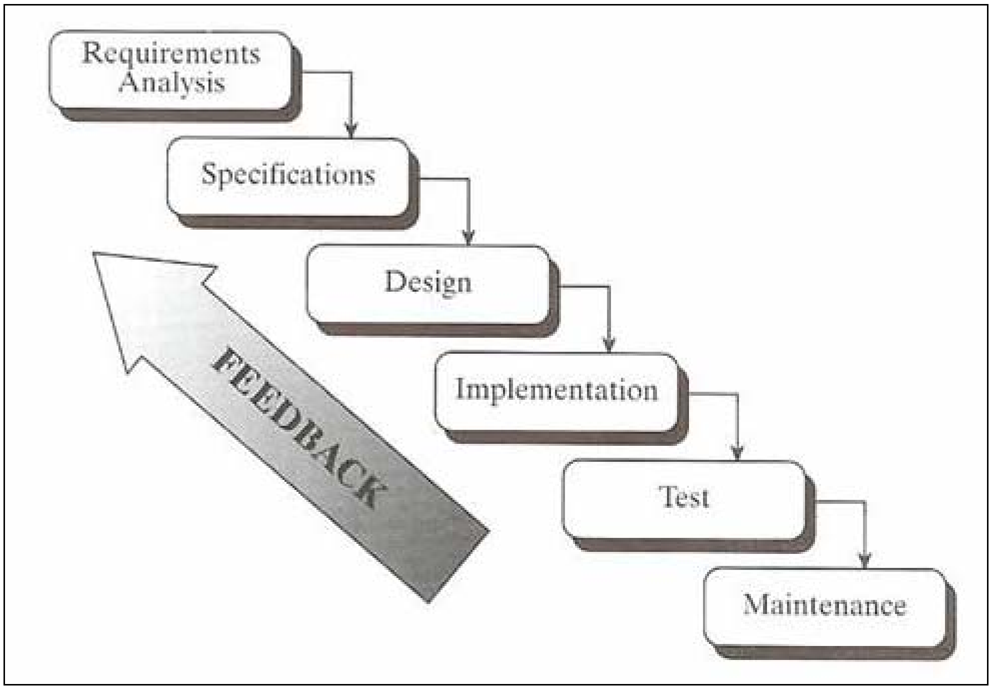

Figure 5. SABR Systems Engineering Process Model

For the purpose of the SABR project, the waterfall model had to be modified. Since the SABR project ends with a preferred system design concept and not a physical development, the process is not used past the Design phase. Instead amplifications have been made and the phases have been broken down into the steps needed to end with a preferred system design as seen in Figure 6. Further amplification of the process breakdown can be seen in the appendices.

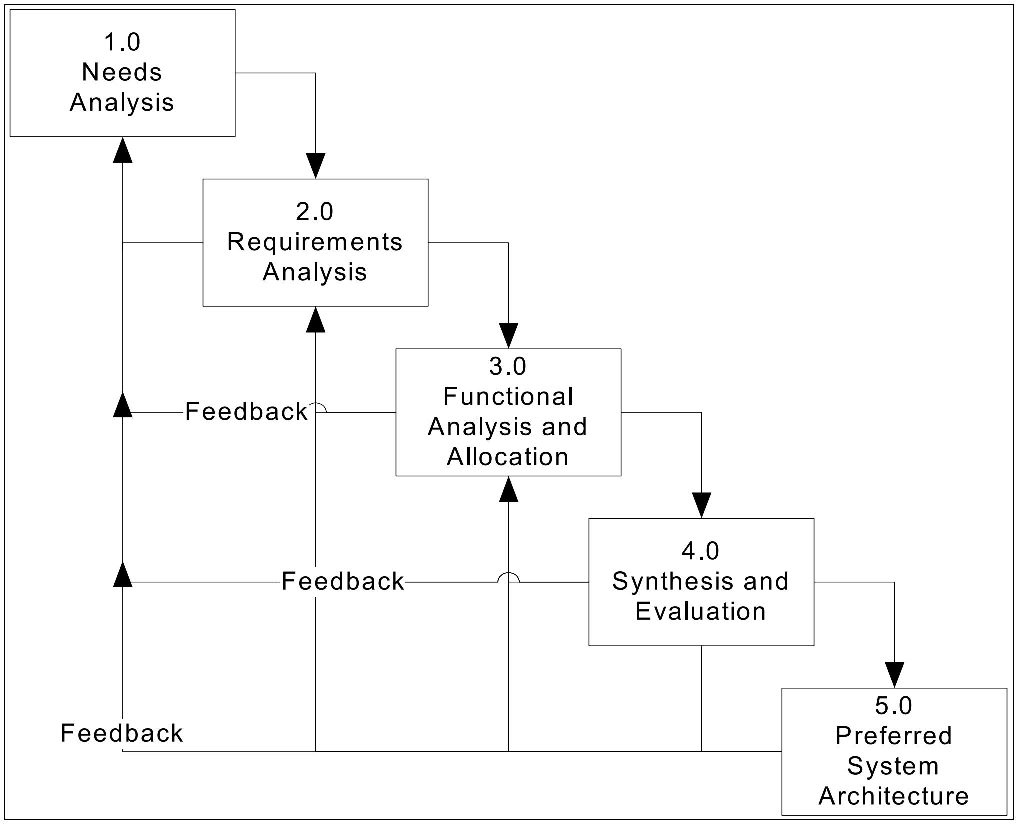

Figure 6. Blanchard and Fabrycky's Basic Waterfall Process Model

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3.0 SYSTEM NEEDS

3.1 THE BALLISTIC MISSILE (BM) THREAT

BM proliferation has become a significant issue in the past 20 years. This situation has developed as more nations have been afforded the opportunity to purchase missiles as a result of the former Soviet Union selling large portions of its missile stockpiles and missile technology in an effort to bolster its failing economy. In addition to the former Soviet Union, rogue nations like North Korea continue to supply missiles and missile technology to virtually anyone who can pay for the information or weapons. This willingness to sell missiles and technology for either monetary or political reasons (or both) has created a weapons market unlike any other.

As a result of this flood of weapons being available to rogue nations and the proliferation of missile technology from the former Soviet Union to states such as Iran and North Korea, the world has become less safe and the Western world must increase its efforts to suppress the acquisition of missiles and missile technology.

3.1.1 Project Threat Definition

A BM is a weapon that follows a prescribed course that cannot be significantly altered after the missile has burned its fuel (its course is governed by the laws of ballistics). In order to cover large distances, BMs are usually launched very high into the air or in space, in a suborbital spaceflight; for intercontinental missiles the altitude halfway through the flight is 1,200 km. Once in space, after more thrust is provided, the missile goes into freefall.

BMs are not new and have been effectively employed in combat by nations since World War II. In fact, the Nazi regime of Adolf Hitler effectively used the V-2 Rocket as a weapon of terror during the war,[24] when many as 3,225 were launched in combat, primarily against Antwerp and London."[25] The Iranians and Iraqis exchanged volleys of missiles in their near decade-long war. More recently, the Iraqis used their indigenous

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[24] http://www.flyingbombsandrockets.com/V2_intro.html, 4 April 2006.

[25] http://www.astronautix.com/lvs/v2.htm, 4 April 2006.

variant of the Soviet-developed SCUD missile against Israel and Saudi Arabia. The primary difference between today's weapons and their predecessors is in the realm of accuracy. Today's weapons are accurate to within meters, whereas older weapons, specifically the V-2s employed against Great Britain in World War II, experienced a Circular Error Probable (CEP)—the radius within which 50% of the shots' impact of 12 km[26] (as determined through accuracy analysis data based on the number of missiles launched, their intended targets, and the impact distance from the intended target).

Many missiles are available on the world arms market and the BM is the most threatening of all, due to the devastating effects of the various payloads a weapon of this type is capable of delivering. Although conventional payloads were used with great effect in past conflicts (Gulf War, Iran/Iraq War, and World War II, respectively), the conventional payload did little physical damage when compared to the psychological terror ballistic missiles had on the populations they were used against, specifically Israel in the 1991 Gulf War.

A fact of particular note is that:

> The damage caused by the 39 Iraqi Scud missiles that landed in Tel Aviv and Haifa was extensive. Approximately 3,300 apartments and other buildings were affected in the greater Tel Aviv area. Some 1,150 people who were evacuated had to be housed at a dozen hotels at a cost of $20,000 per night.[27]

This evidence not only substantiates the claim of BMs as weapons of terror, but places a dollar value on the cost of being attacked by such weapons.

> Beyond the direct costs of military preparedness and damage to property, the Israeli economy was also hurt by the inability of many Israelis to work under the emergency conditions. The economy functioned at no more than 75 percent of normal capacity during the war, resulting in a net loss to the country of $3.2 billion.[28]

From this, it can be concluded that the BM has significant value as a weapon of terror regardless of the warhead it carries. This fact is evidenced by the uneasiness

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[26] http://www.astronautix.com/lvs/v2.htm, 4 April 2006.

[27] http://www.jewishvirtuallibrary.org/jsource/History/Gulf_War.html, 4 April 2006.

[28] http://www.jewishvirtuallibrary.org/jsource/History/Gulf_War.html, 4 April 2006.

experienced by the world powers when considering those nations that have the potential to possess or that do possess BMs.

3.1.2 Case-In-Point: North Korean Missile Systems

Although there are a myriad of potential threats to Western nations regarding BMs, one of the most likely threats is from the North Korean Taepo Dong missile or some derivative thereof. This is evidenced by North Korea's 31 August 1998 firing of this missile, which flew over the Japanese island of Honshu and landed roughly 330 km away from the Japanese port city of Hachinohe after flying for approximately 1,320 km.[29]

Another factor taken into consideration, beyond the knowledge of a nation possessing BMs, is the likelihood of proliferation of the technologies possessed by North Korea. Such proliferation of missile technology has occurred between the nations of Pakistan, Iran, North Korea, and the People's Republic of China (PRC). As this technology was transferred between the aforementioned nations, it is assumed that there will be a significant commonality in the missiles possessed by those nations. As a result, it is assumed that the common threat technology, regardless of the nation of origin, will possess the majority of characteristics of the North Korean Taepo Dong missile. Therefore, the basis of the information regarding threat and political motivation to employ weapons will mimic the approach of North Korea.

The North Korean regime under Kim Jong Il has displayed a propensity to provide any nation requesting assistance with information regarding missile development technology. This willingness, in conjunction with the collaboration of efforts with the Iranian/Pakistani/Chinese missile programs, has significantly increased the likelihood of BMs being used against Western interests in the future. As a result of this situation, western powers must continue their efforts in developing a BMDS capable of effectively neutralizing the near-term threats. If this does not occur, there are potential security ramifications for decades to come.

The Taepo Dong 2 is a three-stage, liquid-propellant, surface-based Intercontinental Ballistic Missile (ICBM) capable of ranges up to 4,300 km. The

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[29] Monterey Institute of International Studies, http://cns.miis.edu/research/korea/factsht.htm, Monterey, CA, 2006.

Taepo Dong 2 missile is a likely threat due to the nation that possesses it, the probability that the technology will be transferred (or has already been transferred) to nations not friendly to Western powers, and the perceived likelihood of one of those nations employing the weapon.

3.2 CURRENT (2006) SEA-BASED BMD CAPABIILITIES

Defense against BMs has been a prime national security objective for nearly 30 years. Significant research and funding were allocated as part of the Strategic Defense Initiative (SDI), a significant program and part of the defense buildup undertaken by the Reagan Administration in 1981-1989. While no systems were fielded as a result of this research, significant scientific advancements were made in related fields.

The need for regional BMD became more apparent in the 1991 Gulf War. Iraq's use of SCUD missiles against targets in Saudi Arabia and Israel presented coalition forces with a threat for which there was no dedicated countermeasure. U.S. Army Patriot missile systems, designed to shoot down conventional aircraft, were modified and pressed into service as a last ditch defensive measure. This solution was far from optimal, however. Engagement was only possible while the enemy projectile was in the terminal, or reentry, phase of flight.[30]

In the years since this conflict, there has been considerable investment and research on the BMD problem. In the short term, the U.S. military in general, and the U.S. Navy in particular, has sought to retrofit currently fielded systems to provide an initial BMD capability. As of 2006, significant progress has been made.

3.2.1 Maritime Component of Current U.S. BMD Efforts

The U.S. Navy had initial technological success with modifying the Aegis weapons system. This program has sought to improve the already impressive detection capabilities of the AN/SPY-1 series of shipboard phased array radars. The physical

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[30] Steven A. Hildreth, "Evaluation of U.S. Army Assessment of Patriot Antitactical Missile Effectiveness in the War Against Iraq," Specialist in National Defense, Foreign Affairs and National Defense Division, Congressional Research Service. Prepared for the House Government Operations Subcommittee on Legislation and National Security, 7 April 1992.

transmitters and receivers of this system are highly capable. The supporting software was initially designed to filter out extraneous data resulting from these capabilities; detection of exo-atmospheric tracks was considered an impediment to the systems design capability of anti-air warfare. Now, software modifications have been developed to accurately process and track exo-atmospheric objects. U.S. Navy Aegis warships are equipped to operate off of the coast of potential threat nations, acting as early-warning assets and communicating with a worldwide network to counter a possible BM launch against the United States.

Alongside the sensor development, the Navy and the aerospace industry have been developing a ship-launched, exo-atmospheric, interceptor missile. Currently in testing is the SM-3, a derivative of the widely fielded Standard Missile. The SM-3 has a series of successful test intercepts to its credit, but has yet to be deployed to frontline assets.

3.3 NEEDS ANALYSIS

The SE process as a whole starts with the identification of an aspiration, want, or need. This need is developed or defined from a noticed deficiency in an as-is system, or a lack of capability. The system needs should give a good representation of what stakeholders want or desire as a system performance outcome. These needs are then used to derive traceable top-level requirements, MOEs, MOPs, and functions to be used in system development.

3.3.1 SABR System Needs

The definition of the system needs for the SABR project are derived from several different areas. First, the tasking statement, gives specific design criteria for the SABR system.

- Create a ship-based BMD system architecture.
- Use emerging criteria for SR to MR threats.
- Integrate with coalition partners.
- Contribute to the whole of layered BMD.

System bounding assumptions and scope have been imposed on the project, and the system needs definition must fit them. Next, using the tasking statement and bounding assumptions the SABR team identified current and future BM threats and defense capabilities.

The development of the needs statements have been through many revisions. Initial problems have come from not having a well-defined set of stakeholders or customers available. By not having a customer, the SABR team has had to act as the customer and decide what the possible "wants" of the system needed to be. Various faculty members and visitors have served as verifying and validating agents to ensure that the needs statements actually fit the desires of the institute for the project. Other problems have been encountered during the definition of the system need such as keeping the statements general and the solution neutral. With regard to this phase of the project, needs analysis was one of the most difficult hurdles the SABR team had to overcome due to the extremely focused tasking statement.

Six system needs statements have been defined.

1. Protect coalition partners from BM threat.
2. Operate independent of nation-state territorial boundaries.
3. Employ over a wide range of environmental conditions.
4. Assimilate into the integrated, layered BMD system.
5. Interoperate with coalition partners.
6. Destroy TBM system with a high probability of kill.

Using these need statements the SABR team was able to begin identifying solution-neutral requirements and technical performance measures. Scenarios were also developed in the Design Reference Mission (DRM) that would address the needs of the SABR system.

3.4 DESIGN REFERENCE MISSION (DRM)

The DRM has been developed to define the environment in which the system will be working, in a language that is understandable by stakeholders and the SABR team alike. The DRM is an SE design tool that defines the problem, not the solution. The DRM takes critical technical performance measures and develops scenarios in which certain factors are considered. First, a Design Reference Mission Profile (DRMP) was developed. Next, stressed operational factors were identified. These factors were input into the DRMP. Three scenarios were chosen: best, most likely, and worst case. The worst case scenario is the stressed scenario, which puts the most limitations on the system. The best case scenario is the basis for the initial modeling efforts. The model developed for the best case scenario was altered to determine what types of changes need to be made and how to alter SABR's concept of operations in order to reflect the stressed scenario. All scenarios are realistic and possible. Stressed factors are divided into two groups: naturally induced and human induced. Examples of naturally induced stressing factors are weather, sea state, geography, atmospheric ducting, and topography. Examples of human induced stressing factors include launch location, number of threats launched, systems status, and weapons available.

Scenario 1

Scenario 1 is the SABR team's best case, or least stressed, scenario as seen in Figure 7. This scenario is a perfect world in which all environmental and human induced stressing mechanisms minimally affect the system. The threat's location is known. There is only one missile threat. The threat is launched near the shore. There is no cloud cover and the sea is calm. All sensor systems are functional and the network is functional. There is no delay in the transfer of data; therefore, the system is operating in a real time environment. All weapon systems are on-line and available. Satellite detection is instantaneous. The ships are able to detect the threat as soon as it reaches the radar horizon. Engagement authority is preauthorized if the threat meets the requirements.

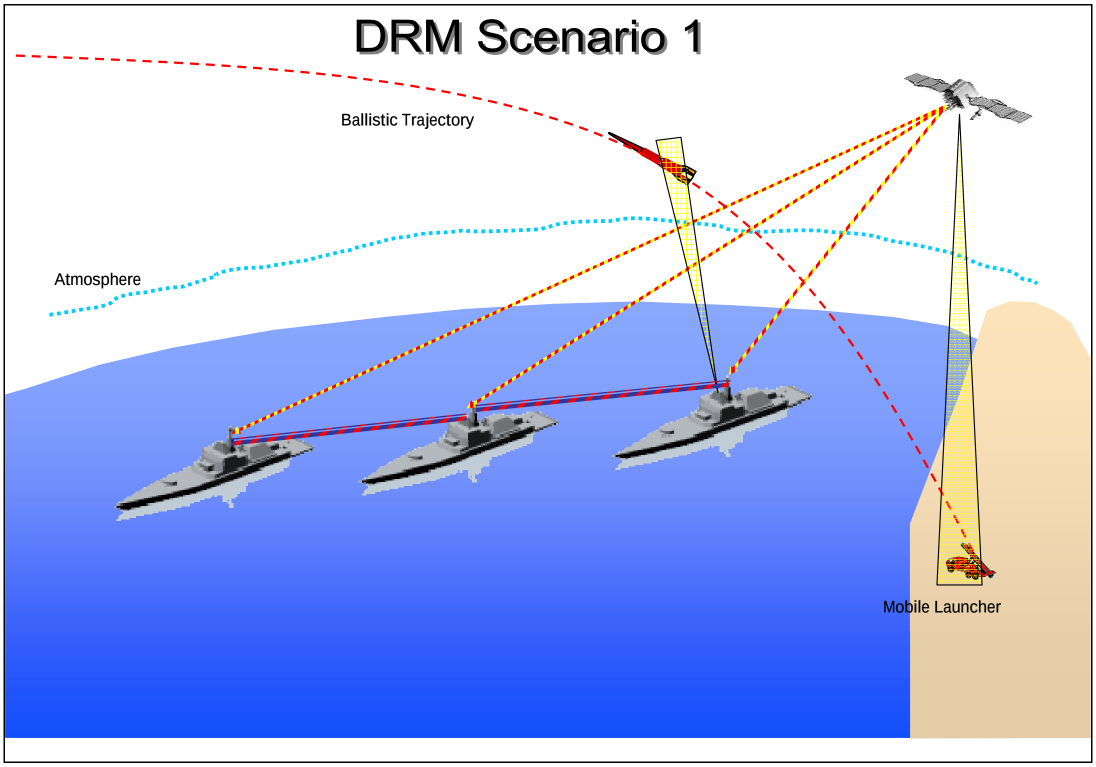

Figure 7. Least Stressed Scenario

Scenario 2

Scenario 2 is a more stressed scenario as seen in Figure 8. There is 100% cloud cover. Satellite detection will not occur until after the threat has cleared the cloud layer. There are two threats launched from two different locations. The threats are launched 50 NM inland. All weapon systems are on-line and functional. The network is functional; however, there is a delay in data transmission and, therefore, the system is less than real time. Ship sensors are functional and are able to detect the threats as soon as they reach radar horizon. Engagement authority is preauthorized if the threat meets the requirement.

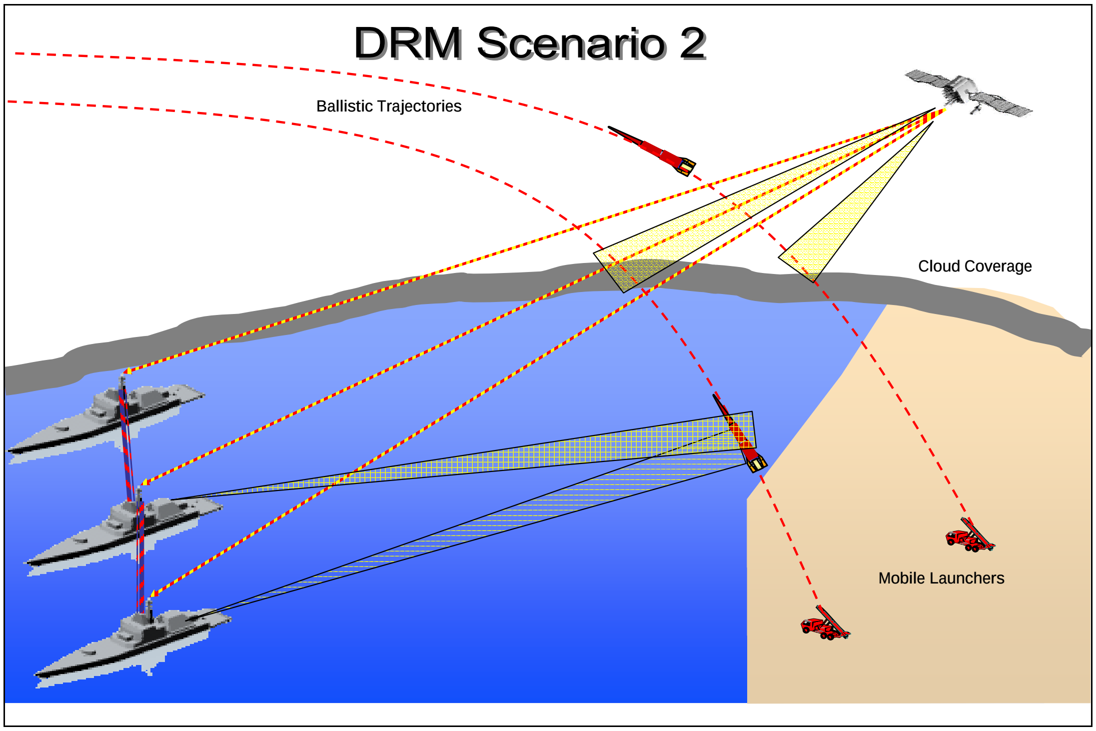

Figure 8. More Stressed Scenario

Scenario 3

Scenario 3 is the most stressed scenario as seen in Figure 9. This scenario will fully exploit the limitations of the system and will further identify the systems short comings. There is complete cloud coverage. Sea state is rough with large swells (sea-state 5). The network is down; ships can only fire on their own fire control data. Satellite detection is not functional. Own ship sensors are functional and are able to detect the threat as soon as they reach radar horizon. However, since the collaborative information exchange system is down, if one part of a ship system is down then it is not functional. There will be multiple threats launched from multiple sites. The threats are launched from deep inside the threat territory and are masked by terrain. Engagement authority is required from the local BMD commander.

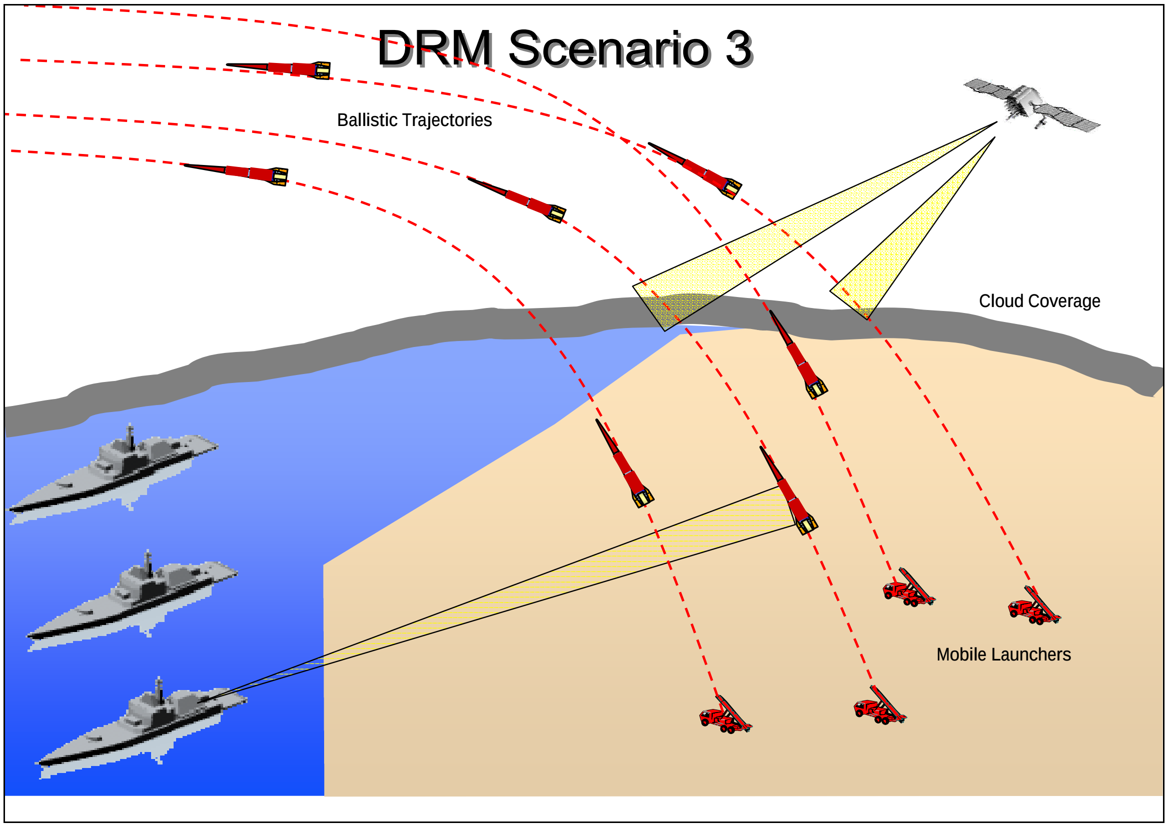

Figure 9. Most Stressed Scenario

4.0 REQUIREMENTS ANALYSIS

4.1 SYSTEM REQUIREMENTS

After the definition of the system needs statements, focus shifts to the development of system requirements. As with the system needs statements, the system requirements also need to be solution neutral, completely describe the system to be developed, and be traceable back to the system needs. The system requirements describe the “whats,” not the “hows,” of the system. The requirements, in conjunction with the MOEs and MOPs, are used to develop a functional system description.

Like most systems engineering processes the development of the system requirements is also iterative. When defining the systems requirements the SABR team kept in mind that requirements come from a variety of different sources. With the SABR project, one source for requirements development is the needs that were defined during the needs analysis phase.

Brainstorming initially produced somewhere in the range of 50-60 different system requirements. Upon first inspection, they all seemed to be legitimate. However, after further analysis, some statements appeared to be redundant, solution specific, or immeasurable. After many iterations, a final set of system requirements was generated. The final set of top-level requirements is:

- Rapidly deployable, sea-based platform capable of prolonged operations.
- Stable platform capable of operations in heavy seas.
- Detect and track over-the-horizon BM launch and flight path.
- Share real-time sensor, weapon, fire control, and BDA data among coalition forces.
- Prioritize threats and optimally pair assets with the highest probability of kill.
- Designate targets with a low probability of kill to other assets.

To validate the requirement statements and ensure that every need had been met, a QFD House of Quality (HOQ) was developed.

In HOQ 1, shown in Table 1, the needs are listed down the left side, representing the "whats." Weights are assigned to the different needs to show a breakout of importance based on customer desires.[31] The requirements are then filled in across the top, representing the "hows." The matrix is filled in using a weighted metric to show relative impact of requirement to need; where 9 reflects a high impact, 3 a medium impact, 1 a low impact, and 0 no impact. The impact value is multiplied by the respective normalized weight for the needs and summed down each column to produce a weighted impact for each requirement. As a quick check that the weighting was not sensitive to possible bias in customer weights, another HOQ1 was created that assigned all of the needs an equal weight. After doing this, it was discovered that the rankings of requirements did not change from the previous weighted rank, therefore showing little to no sensitivity to bias from customer wants on the requirements for system development. From here, HOQs 2, 3, and 4[32] were developed to further define metrics and provide traceability from the needs all the way to the MOEs.

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[31] Since there is no customer for the SABR project, the weights were assigned by the project faculty advisor, Professor Clifford Whitcomb.

[32] All of these HOQ diagrams can be found in Appendix A.

Needs (What's)	*Weights*		*Requirements/Capabilities (How's)*						
			Rapidly deployable sea based platform capable of prolonged operations	**Stable platform capable of operations in heavy seas**	**Detect and track over the horizon ballistic missile launch and flight path**	**Share real-time sensor, weapon, fire control, and BDA data among coalition forces.**	**Prioritize threats and optimally pair assets with highest probability of kill**	**Designate targets with a low probability of kill to other assets**	
Protect coalition partners from ballistic missile threat	0.2727	0.273	**3**	**1**	**9**	**9**	**9**	**9**	
Operate independent of Nation State territorial boundaries	0.0909	0.091	**9**	**1**	**9**	**0**	**0**	**0**	
Employ over a wide range of environmental conditions	0.1364	0.136	**9**	**9**	**9**	**3**	**3**	**3**	
Assimilate into the Integrated Layered BMD system	0.0909	0.091	**0**	**0**	**9**	**9**	**9**	**9**	
Interoperate with coalition partners	0.1364	0.136	**0**	**0**	**0**	**9**	**9**	**9**	
Destroy TBMS with a high probability of kill	0.2727	0.273	**1**	**9**	**9**	**9**	**9**	**9**	
Check Sum		1.00							
Goal Value									
Threshold Value									
Weighted Performance			3.1	4.0	7.8	7.4	7.4	7.4	37.0
Percent Performance			0.085	0.109	0.210	0.199	0.199	0.199	

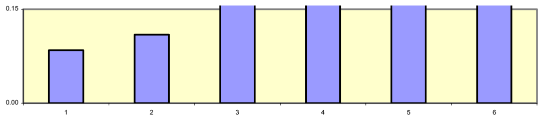

Table 1. QFD HOQ 1 System Needs to System Requirements

4.2 OPERATIONAL CONCEPT

The SABR team's BMD project involves a complex and detailed system. The individual components are described in other sections, but the process as a whole is best shown in Figures 10 through 14.

Based on modeling and information provided through operations research techniques, a standard Naval Task Unit for an effective BMD force, equipped with an effective BM interceptor, consists principally of three warships. It is assumed that intelligence-gathering efforts and the geo-political situation will permit sufficient time (measured in weeks) for decision makers to deploy assets to observation positions in the region of the threat area. These warships are equipped with the conformal hull-mounted, phased array radar system for organic, long-range detection. Supplementing this onboard system are nonorganic detection and early-warning assets, principally satellites designed to detect missile launches through the use of EO detection equipment. This initial setup is shown in Figure 10, with the satellite shown in the upper left-hand corner, orbiting over a nation that has threatened a BM launch. The BMD Task Unit ships are stationed at different locations and distances off of the coast.

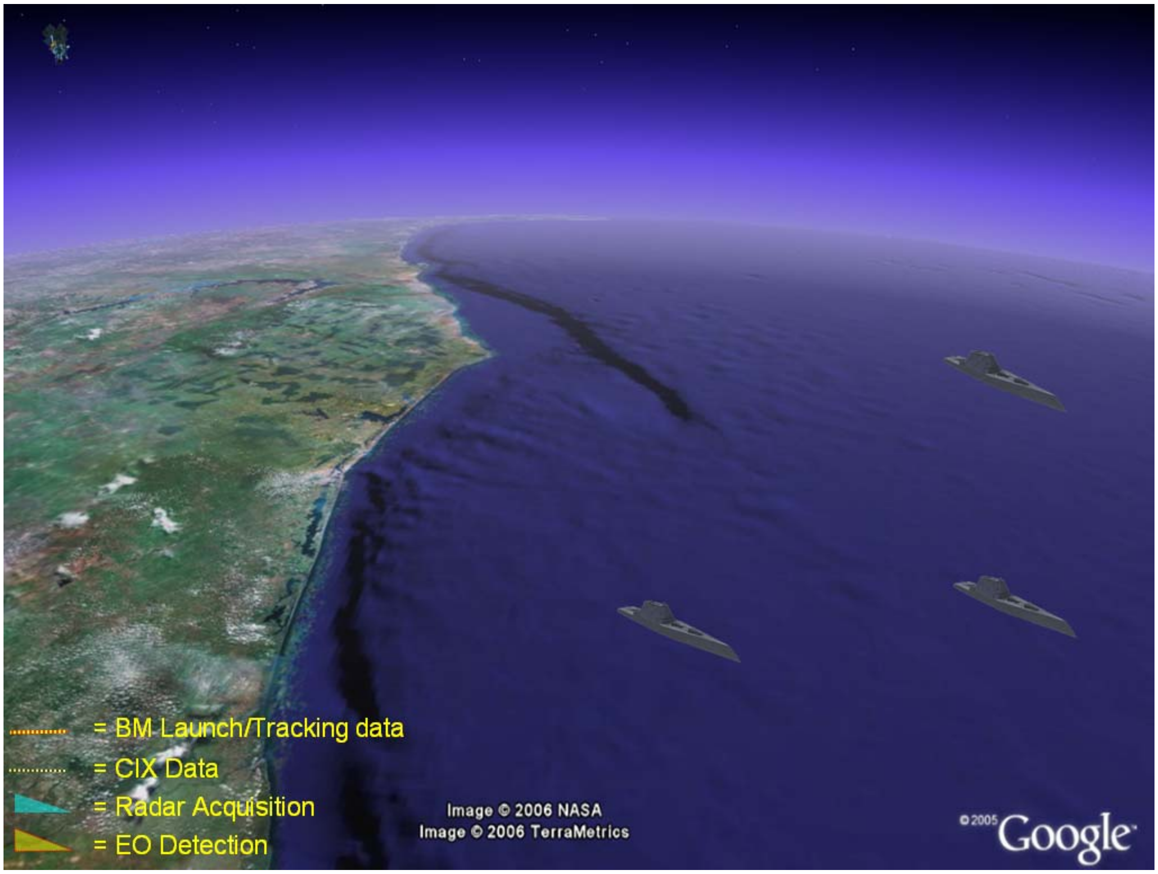

Figure 10. Naval BMD Task Force Stationed Off Coast, Monitoring for Missile Launch[33]

Should a BM launch occur, the expected sequence of events is analogous to the standard Air Defense "Detect-to Engage" sequence. This sequence consists of the following steps:[34]

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[33] Google Earth, Copyright 2006, Image modified 2 February 2006.

[34] United States Naval Academy, Air Warfare Training Presentation, www.usna.edu.

A. DETECTION
B. ENTRY
C. TRACKING
D. IDENTIFICATION
E. THREAT EVALUATION
F. WEAPONS PAIRING
G. ENGAGEMENT
H. ENGAGEMENT ASSESSMENT

STEPS A, B: Detection and Entry: A BM launch is detected, most likely by nonorganic assets. This detection is entered into the detection network and queuing information is sent to the "firing units"—the warships stationed offshore.

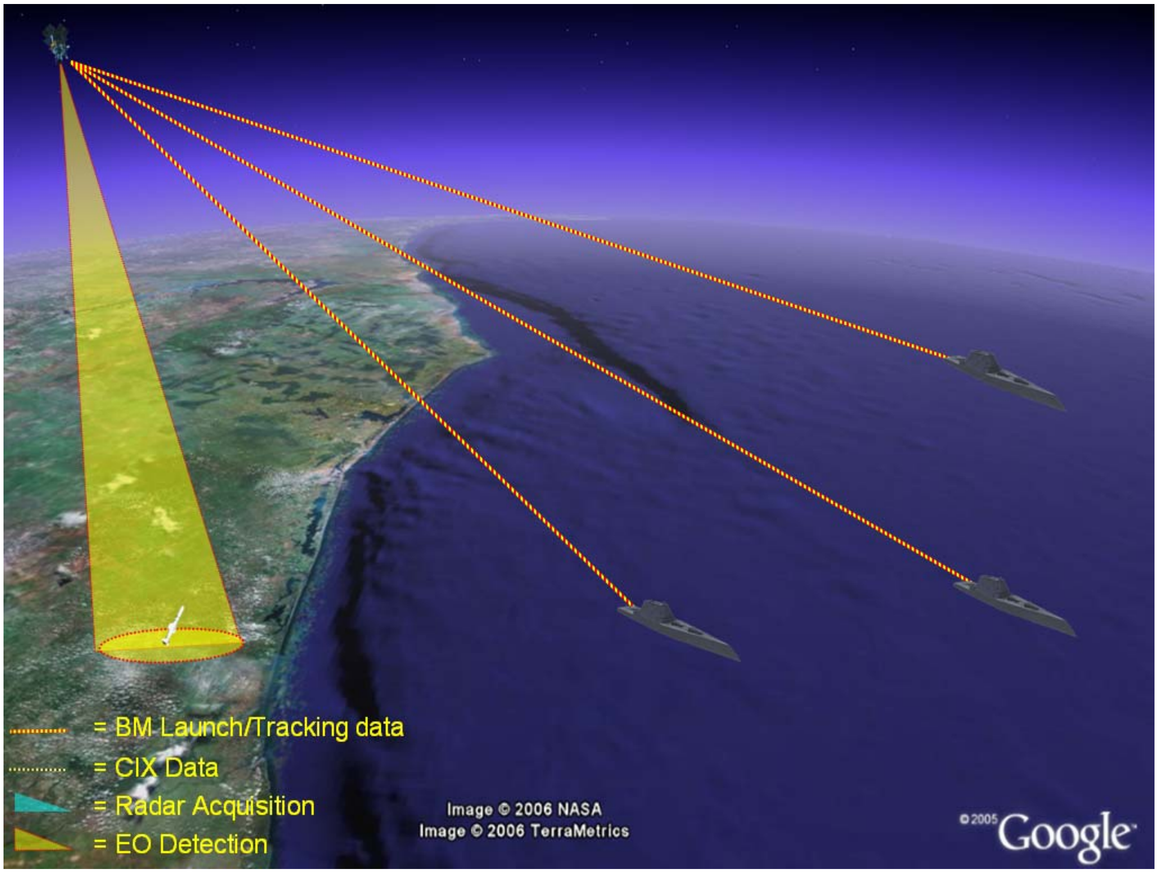

Figure 11. Hostile nation launches missile. The launch is detected by satellite, and this information is relayed to ships off shore.[35]

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[35] Google Earth, Copyright 2006, Image modified 2 February 2006.

STEPS C, D: Tracking and Identification: The target is detected by the nearest warship, and a fire-control solution is generated. This tracking data is shared with other BMD ships via the Collaborative Information Exchange (CIX). The kinematics of the target is analyzed and a determination is made as to whether or not the target being tracked is classified with high confidence as being a BM.

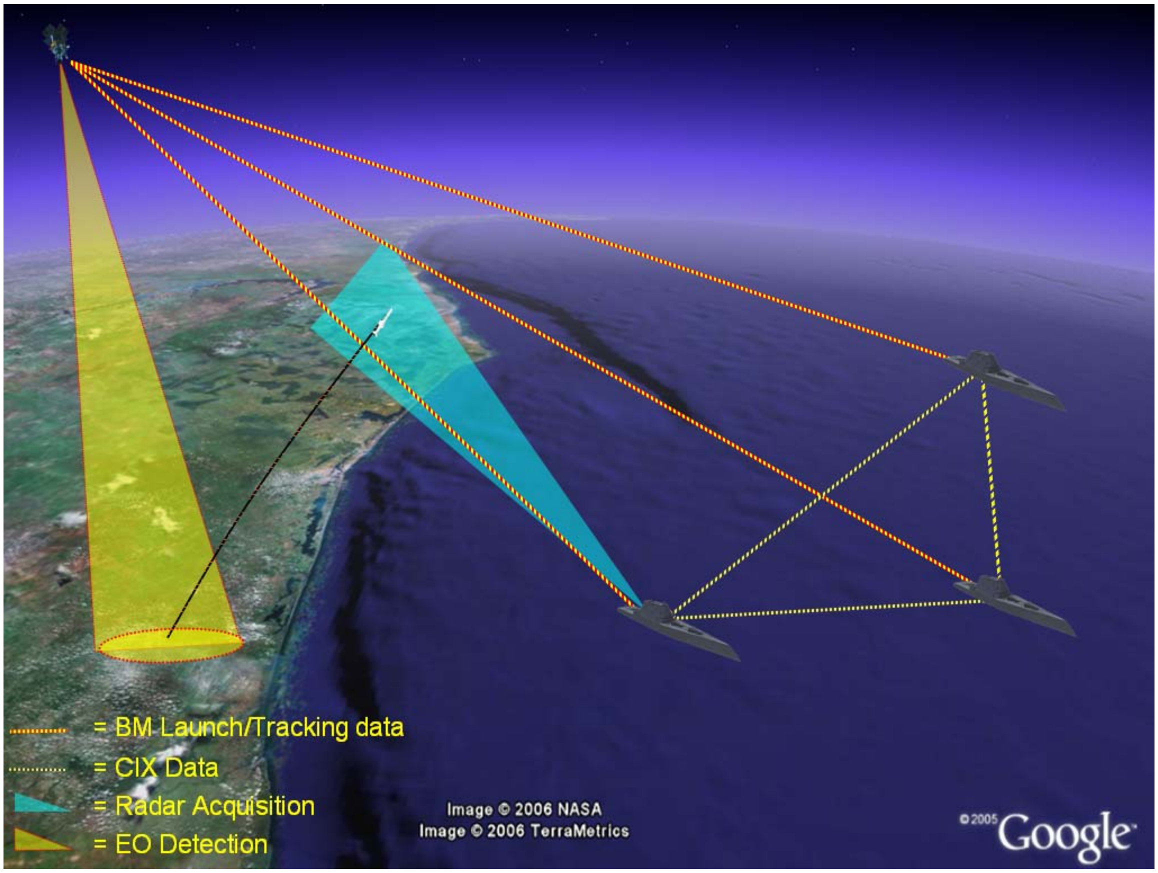

Figure 12. BM is ascending. The nearest ship begins to track the missile and shares targeting information with the other ships.[36]

STEPS E, F: Threat Evaluation and Weapons Pairing: As the firing units track the target, its flight path and threat to potential downrange targets is assessed. Anticipating that the target will be engaged, the best available weapon system and platform are selected. This is based on a system analysis of which platform will have the highest probability of hit and probability of kill (Pk).

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[36] Google Earth, Copyright 2006, Image modified 2 February 2006.

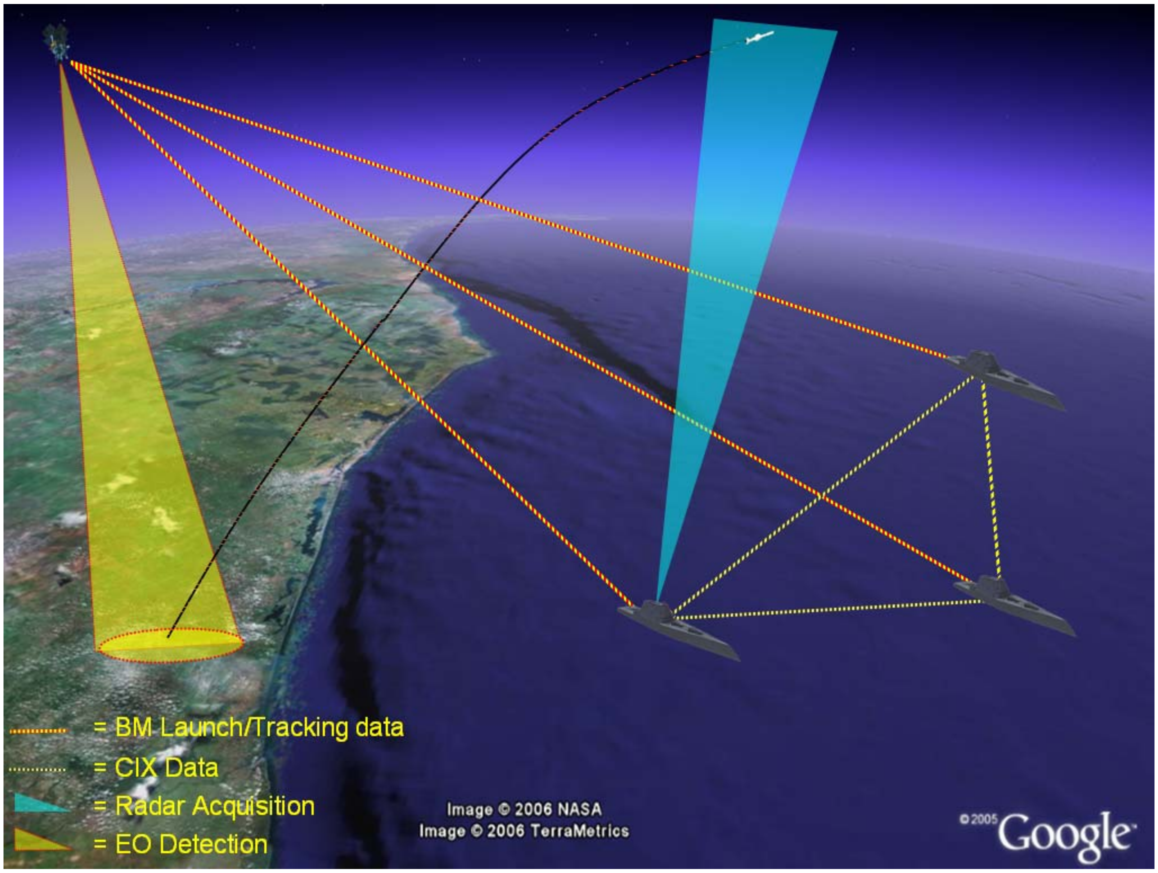

Figure 13. BM continues in flight. Ship that is tracking computes a firing solution and shares this data with the other ships.[37]

STEPS G, H: Engagement and Engagement Assessment: Having determined that the BM is a threat that needs to be engaged, the selected ship will open fire with its railgun. A standard salvo will be four projectiles per engagement, per individual target. One ship, equipped with two railguns, will be able to have all four projectiles in-flight within four seconds (based on SABR project modeling and entering assumptions). Once the anticipated time of flight for the railgun projectiles has expired, tracking systems will assess the effectiveness of the engagement, looking for detection of impact and breakup of the target. If no impact is detected, the fire control system will assess the feasibility of a reengagement, another salvo from the shipboard railgun. If this is possible, another salvo will be fired, and steps G and H are repeated. If another salvo is not physically possible (i.e., the P (Hit) and P (Kill) are too low), the CIX will "hand-off" all tracking data to other BMD assets.

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[37] Google Earth, Copyright 2006, Image modified 2 February 2006.

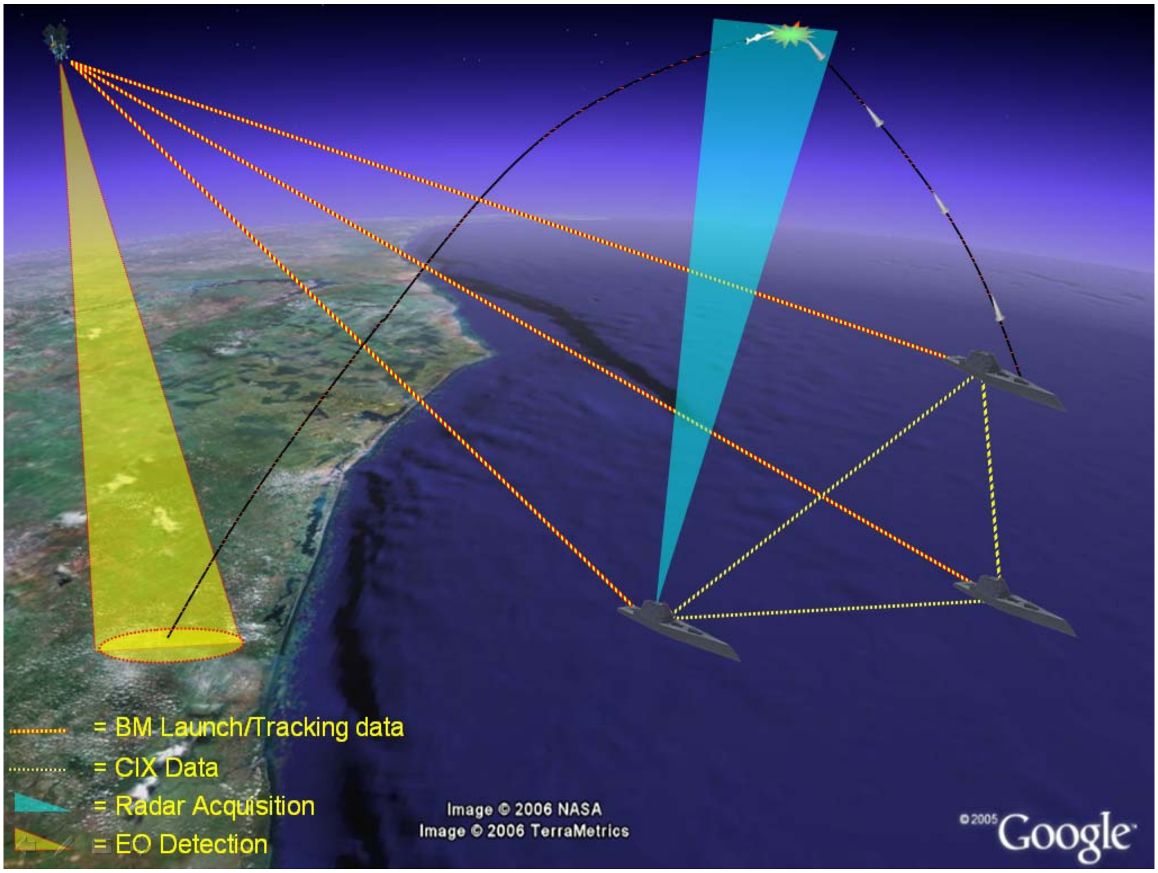

Figure 14. As BM continues its flight, the tracking ship assigns the ship with the highest Pk to engage the missile with interception weapons. This ship fires the weapon and destroys the missile.[38]

4.3 MEASURES OF EFFECTIVENESS (MOES) AND MEASURES OF PERFORMANCE (MOPS)

The definition of the MOEs and MOPs is crucial to the development of the SABR-preferred system design. The MOEs and MOPs provide a quantitative means for the team to determine which of the different architectures is the most effective in conducting BMD. As in every other phase of the SE process, the definition of MOEs and MOPs is an iterative process. It was important that the MOEs and MOPs were specified in terms of importance to the criticality of the functions to be performed by the system. The metrics developed were as follows:

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[38] Google Earth, Copyright 2006, Image modified 2 February 2006.

MOEs:

- Max number of sufficient power supply situations for mission accomplishment per minute
- Max number of missions completed regardless of environmental conditions (wind, seas, and cloud cover) per minute
- Number of days of sustained operations
- Probability of detection (Pd)
- Probability of false alarm (Pfa)
- Probability of correct identification
- Probability of engagement (Pe)
- Pk
- Probability of handoff
- Max number of targets simultaneously tracked and identified per minute
- Probability of worldwide sensor coverage
- Probability of CIX function being operational
- Max number of targets effectively engaged per minute
- Number of successful Battle Damage Assessments (BDA) (good or bad) gathered and processed per minute
- Number of successful Command and Control (C2) decisions made per minute
- Max number of designated target files passed to other assets per minute

MOPs:

- Number of BM simulated
- Number of BM detected
- Number of nondetections
- Number of false alarms
- Number of handoffs
- Number of engagements
- Number of simultaneous engagements
- Number of failed engagements

- Mean nonorganic detection time
- Mean time to relay detection
- Mean time to process detection
- Mean organic detect time
- Mean track formulation time
- Mean time to identify
- Mean threat prioritization time
- Mean weapons pairing time
- Mean engagement time
- Mean time from detection to BDA
- Mean time to conduct BDA
- Mean time available for reengagement
- Mean time to end of midcourse

The same method of using a QFD HOQ is used to define the MOEs and MOPs. A HOQ 2 was constructed to examine the relationship of the requirements as they relate to the different MOEs. This provides a method to ensure that every system requirement has some method of being quantitatively measured and allows the team to establish a level of importance for analysis. From here, HOQ 3 was constructed showing a traceability from the MOEs to basic solution neutral top-level functions. HOQ 3 helped the team to begin determination of what functions needed to take place in order to meet the expectations delineated by the system needs. It also aided in ranking the functions to determine which functions are critical for system success. HOQ 4 followed showing the relationship between the functions and the MOPs. As with HOQ 2, HOQ3 provided a breakout of the MOPs establishing a ranking to determine a level of importance to the system for analysis.

These MOEs, functions, and MOPs became direct components of the simulative analysis models. Once implemented into the models, the MOEs and MOPs provide information on each of the system architectures and provide a method of ranking one system's architecture against another. This allowed for tradeoffs analysis among the different systems to determine the preferred architecture.

5.0 FUNCTIONAL ANALYSIS, ALLOCATION, AND MODELLING

5.1 SHIP ANTI-BALLISTIC MISSILE RESPONSE (SABR) FUNCTIONAL ANALYSIS AND ALLOCATION

The objective of the functional analysis process is the creation of a functional architecture based on technical requirements in appropriate solution neutral terms to guide the development of alternative physical architectures in the system synthesis process. Functional analysis is an iterative process that starts with the defined system requirements and the initial identification of the top-level functions of the system and decomposing them to subsystem levels. The definition of the top-level system functions for the SABR project began by using QFD HOQs. These QFD HOQs were used to translate the functions from requirements, MOEs, and MOPs. The result of this was the following top level functions for the SABR systems to accomplish.

- Receive intelligence cueing
- Acquire nonorganic asset information
- Acquire/detect target
- Track target
- Identify target
- Generate fire control solution(s)
- Make C2 decision
- Engage BM
- Exchange information
- Gather and process BDA

Using these top-level functions, the SABR team decomposed the system into sublevels creating different FFBDs to depict how the various top-level functions could be achieved.

Moving on from functional analysis into functional allocation, the “whats” are converted into the “hows.” During this process, similar functions are grouped together and different design approaches to achieve those functions are developed. After establishing several different design approaches to achieve the functions and meet the needs of the system, tradeoff studies are conducted. In the end, the tradeoff studies give way to a preferred system design architecture for the SABR system.

The functional analysis and functional allocation process used is discussed, showing how different FFBDs are used to describe and decompose the system functions and kill chains. Details are provided as to how the system functions can be achieved via a combination of different physical systems and different design approaches.

5.2 FUNCTIONAL ARCHITECTURE DEVELOPMENT

5.2.1 Requirements for the Support Vessel

The SABR system is a sea-based BMD platform for the defense of U.S. and allied assets. In order to support the sensor and interceptor systems, the vessel that carries and supports these functions must be designed to meet specific system needs.

The ship must be able to sustain operations under severe environmental conditions. Although a relatively calm area of operations, the Arabian Sea, for example, can experience sea states up to level 6 under certain weather conditions, other potential areas of operation, such as the South China Sea, Yellow Sea, North Atlantic, and others, have the potential to be much more environmentally hostile. Operating successfully under these conditions will necessitate the use of a stable hull design with high endurance and the ability to operate independent of support assets due to the nature of the BMD mission. The following is a description of the platform component in moderate detail.

Hull, Mechanical, and Electrical (HM&E) components of the platform need to support lengthy on-station periods. The sea frame must be a stable sea-keeping platform. It must effectively operate in seas up to and including Sea State 5: 30 knots sustained winds and 18-foot seas. This is based on mission requirements for continuous on-station operations in adverse weather conditions.[39] Sea keeping is a factor in real-world, sea-based BMD operations, with ships occasionally leaving assigned patrol stations and proceeding to port due to heavy weather. The platform must be capable of 30 days of on-station operations (not replenished), and up to 90 days of on-station operations if supply assets are available, again, based on mission requirements for operating

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[39] http://en.wikipedia.org/wiki/Sea_State

independently for extended periods. It must interface with all existing Underway Replenishment (UNREP) systems and rigs, both U.S. and allied. This encompasses rigs for petroleum products, fresh water, cargo, and ammunition.

High speed capability will be needed for transit to and from the designated patrol region (25 kts sustained). The vessel will require an unreplenished cruising range of 5,000 NM at 16 kts,[40] with a low fuel-consumption capability for loitering in patrol regions for extended periods of time. Bow and stern thrusters will be installed to permit maximum lateral maneuvering capability, maximum flexibility in harbor maneuvering situations, and to alleviate some need for the use of harbor tugs—a significant issue if a short-notice sortie is necessary. Overall draft will not exceed 20 feet (approximately 7 meters). This permits entry into a greater number of ports worldwide for resupply and pier side maintenance. Sufficient Ship's-Service Generator capacity to produce a power output supporting continuous high-power operation of radars, communications, environmental and propulsion systems will also be essential. Also, the excessive power consumption of some proposed BMD interceptors, such as DEWs and railguns, must be accommodated.

Like all frontline U.S. Naval warships, aircraft and small-boat facilities are needed for defensive measures, collateral duties, and in this case, for the support and completion of the overall mission of successful BM interception. Such facilities will include being capable of embarking one helicopter of at least MH-60R/MH-60S size, weight, and dimension with a hangar facility for maintenance and storage. A flight deck of sufficient size and weight will be needed to land at up to one MH-53E or one MV-22 aircraft, to support long-range Vertical On-board Delivery (VOD). Furthermore, facilities and provisions for at least two embarked small boats, nominally one 11-meter Rigid Hull Inflatable Boat (RHIB) and one 7-meter RHIB are necessary to be used for force protection, search and rescue, and personnel transfer.

For self-defense weaponry, a variety of weapon systems should be considered. For short-range anti-surface and anti-air defense, one deck gun, similar in performance to the MK 45 series 5-inch (127 mm) weapon system, should be included. Additionally, a short-range missile system to defend against hostile aircraft, missiles, and small surface

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[40] http://www.naval-technology.com/projects/ticonderoga/

craft is necessary. For close-in defense, a Block 1 B Phalanx Close In Weapon System (CIWS) with infrared tracking and antisurface capability,[41] or a successive system of similar specifications, for close-in anti-missile defense and deterrence of the small boat/low-slow aircraft threat.

To satisfy the force protection mission, the design should include installation of an optical surveillance system to support Anti-Terrorism/Force Protection (AT/FP) measures, including multiple remote-controlled, heavy caliber, machine guns, and a rudimentary Anti-Submarine Warfare (ASW) suite for self-defense, to include two torpedo decoys, a hull-mounted, passive detection, sonar system, fire control systems to support Vertically Launched ASROC (VLA), for self-defense purposes. Various smaller personal and crew-served weapons for contingency operations, such as boarding and force protection, will be needed.

Crew complement should not to exceed that of a TICONDEROGA-class cruiser:[42] Ship's company: 24 officers, 340 enlisted; Helicopter Detachment: 6 officers, 25 enlisted, with an additional provision for overflow capability: 6 officer berths, 30 enlisted berths.

The vessel will also field a Vertical Launching System (VLS), nominally matching the design capabilities of the MK 57 VLS, developed for the DDG-1000 program. A minimum of 60 cells will be embarked, to support the deployment of self-defense missiles (the ESSM) and rocket-thrown torpedoes (the VLA), with an open architecture capable of supporting larger and heavier weapons of future designs.

The top-level systems functions are represented in an FFBD. The top-level diagram serves to illustrate the organization of the system, as well as to visually represent the major functions and interfaces. Essentially, each block is a broad function of the system, and the diagram shows the input and output of each block. The functions can be further decomposed and expanded through several iterations, to the desired level of system detail. The diagram should be developed toward the end of the conceptual design phase. Good use of the diagram will ensure that all aspects of the system are considered

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[41] http://www.fas.org/man/dod-101/sys/ship/weaps/mk-15.htm

[42] http://www.globalsecurity.org/military/systems/ship/cg-47.htm

for development, and that all system functions and interfaces are defined and related to each other.

5.2.2 Top-Level Systems Functional Flow Block Diagram (FFBD)

For the purpose of the SABR project, an FFBD, Figure 15 was developed to physically illustrate the top-level systems function.

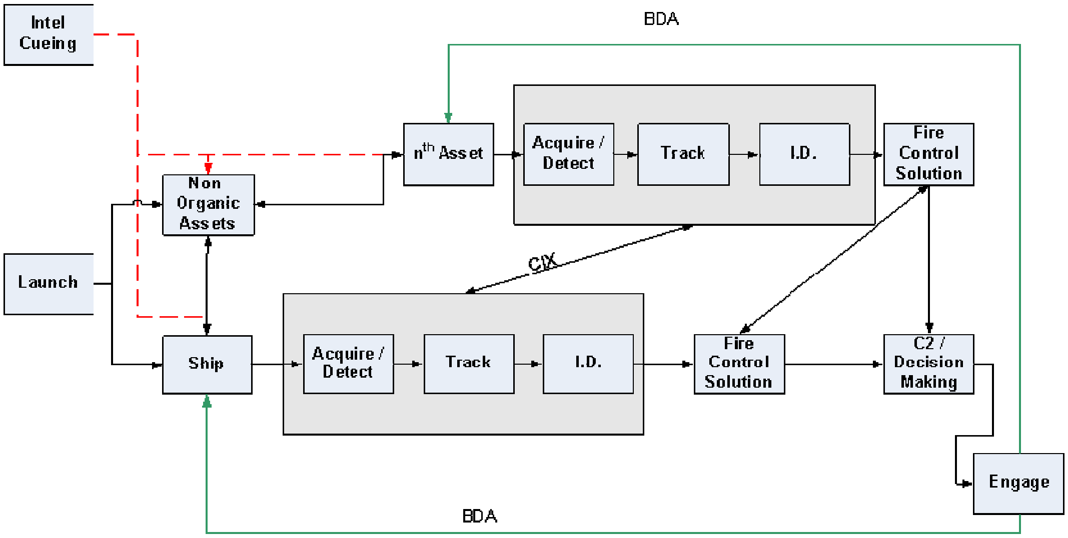

Figure 15. Top-Level FFBD

Each block of this diagram represents an event, or a function of the system.

Intelligence Cueing: Intelligence cueing represents the foreign intelligence aspect of the system, which receives and processes information concerning the threat. This can serve as an early warning that a launch will occur, and is shared with the ship, and nonorganic assets of the system.

Launch: Launch refers to the time and location in which a BM threat is released.

Nonorganic Assets: Nonorganic assets refer collectively to all detecting, tracking, and identification assets that are not located on the ship. Any information gathered by these assets can only be shared with the ship by means of CIX.

Acquire/Detect: The Acquire/Detect function is the initial detection of the missile by the system, either through the ship's radar, or through nonorganic assets. At this point, it may not yet be identified as a BM, but its existence is known.

Track: The Track function refers to determining the missile's current, as well as future, track. At this point, it's identification as a ballistic missile may still not be known.

Identification: The Identification function is the actual identification of a threat as a BM. At this point, it will be identified as a threat. The Acquire/Detect, Track, and Identification functions may be accomplished by either the ship, nonorganic assets, or possibly both. Information may be exchanged through the CIX.

CIX: CIX refers to the collective information exchange, and allows the exchange of information between ships and nonorganic assets.

Fire Control Solution: The Fire Control Solution function may also be accomplished by either non-organic assets, or ships. It consists of determining the flight path for the interceptor to intercept the ballistic missile at a given point in space and time.

C2/Decision Making: The C2/Decision-making function is accomplished through the Automatic Battle Management System (ABMS), which considers the information and fire control solution, as well as assets available, to determine the best way to engage the missile.

Engage: The Engage function refers to the event of actually engaging the BM in order to neutralize it, either through an interceptor missile, or rail.

BDA: BDA determines if the mission was successful. If it was not successful, then the C2/Decision-making function will be used again to determine if the missile will be reengaged or handed off to another asset.

5.2.3 Commit Stage "Kill Chain"

The kill chain is the chain of events that take place in the automated battle management system. Figure 16 is a graphical display of what events occur in the kill chain. The events take place from left to right. There are three end states for the kill chain. The first is a kill order and positive BDA. The second is a kill order and negative BDA or a handoff to another kill evaluation system. If the BDA is negative, then the kill chain process can restart from the beginning. If at any time the system determines that it cannot engage the threat, it will hand off the threat to another missile defense system. This is indicated by the red arrows at the bottom of Figure 16. The red arrow at the top of the figure indicates that the kill chain has started over and will attempt to reengage the threat.

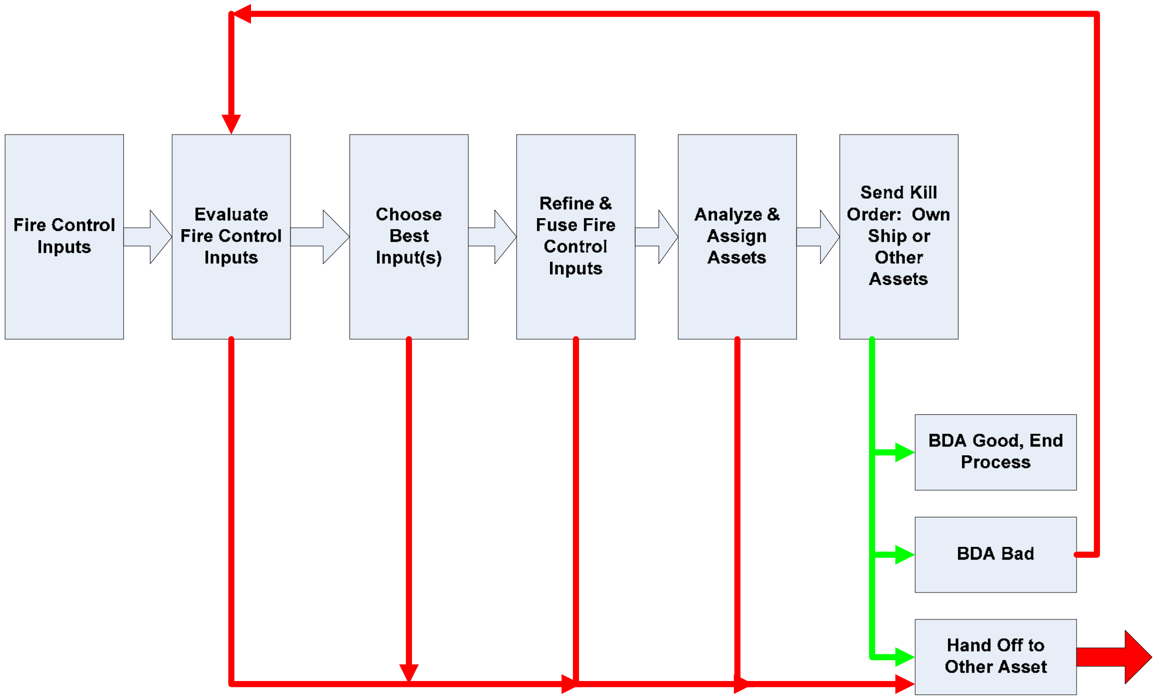

Figure 16. Commit Stage Kill Chain

The first event in the kill chain is receiving fire control inputs. Inputs can come from both organic and nonorganic assets. All threat track information that is sent to the ABMS will be fire control quality data. The reason for only using fire control quality data is to reduce the amount of data sent over the CIX. By decreasing the amount of transmitted data, the cycle time will be reduced. In order for an asset to participate in the ABMS kill chain it must provide a certain quality of track data. The quality of the fire control data must meet the standard for the system. The MDA is utilizing a "Gold Standard" for track data.[43] If the fire control data being sent is not within the standard, it will not be used. Fire control data will be continually updated throughout the engagement.

Next in the kill chain, the ABMS evaluates the fire control inputs. The fire control inputs received are evaluated in order to determine if they meet the standards for engaging the threat missile. The system then chooses the best inputs to be used for the engagement of the threat missile. The system can utilize any asset that is in the area of operation. The system then takes all the inputs that meet the requirements for

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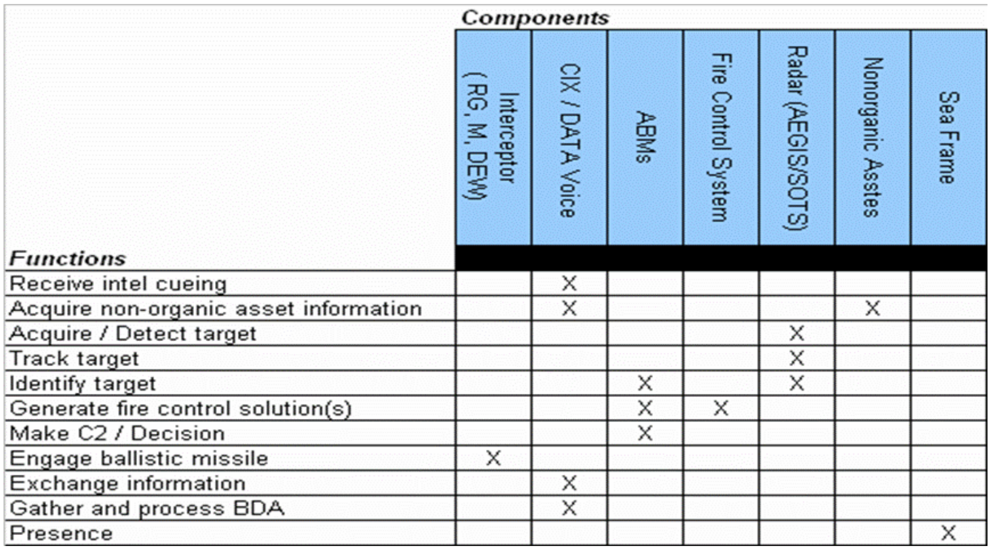
[43] Interview with LTC Thomas Cook, USA, Naval Postgraduate School, Monterey, CA, 3 February 2006.

intercepting the threat missile. From the quality inputs, the system will fuse the inputs into a common track. Fusing the tracks will ensure a higher probability of kill.

The second to last event in the kill chain is to analyze and assign the firing assets assigned to the ABMS. The system determines what firing platform has the highest probability of kill. The system will then assign the firing assets to engage the threat missile. Finally, the kill order is sent to the platform with the highest probability of kill. If the threat is eliminated, and BDA is good, then the kill chain ends. If BDA is bad, and there is enough time to reengage the threat, then the cycle will start over and attempt another engagement. If an engagement is not possible, then the threat data will be sent to another missile defense system.

5.2.4 Functional Allocation

Once the functions of the system are identified, system components are allocated to carry them out. Table 2 depicts the functional allocation table. On the left, each system function is listed and assigned to each component. The top part of the chart lists the system components. On the left, each system function is listed, and they are then assigned to a component.



	Components						
Functions	Interceptor (RG, M, DEW)	CIX / DATA Voice	ABMs	Fire Control System	Radar (AEGIS/SOTS)	Nonorganic Asstes	Sea Frame
Receive intel cueing		X					
Acquire non-organic asset information		X				X	
Acquire / Detect target					X		
Track target					X		
Identify target			X		X		
Generate fire control solution(s)			X	X			
Make C2 / Decision			X				
Engage ballistic missile	X						
Exchange information		X					
Gather and process BDA		X					
Presence							X

Table 2. Functional Allocation

5.3 SHIPBORNE SENSORS

In order for the system to operate continually, and in all theaters, an organic sensor must be developed. The system cannot rely on external or nonorganic sensors only; therefore, it is essential that the ship system include an organic sensor. The sensors must perform the functions of early warning, detection, tracking, fire control, and BDA. The radars must also be capable of sharing data with other BMD assets. Current ship radars do not have the capability to perform the above functions from extended ranges. The group developed a conceptual radar system that is comprised of two separate radar systems that work together to achieve the requirement to intercept a BM threat from a sea-based asset. The radars were specifically designed for BMD; however, they may have the capability to perform other functions as well. Those functions were outside the scope of this project.

5.3.1 Requirements for the Support Vessel

The SABR system is a sea-based BMD platform for the defense of U.S. and allied assets. In order to support the sensor and interceptor systems, the vessel that carries and supports these functions must be designed to meet specific system needs.

The ship must be able to sustain operations under severe environmental conditions; although a relatively calm area of operations, the Arabian Sea, for example, can experience sea states up to level 6 under certain weather conditions. Other possible areas of operation, such as the South China Sea, Yellow Sea, North Atlantic, and others have the potential to be much more environmentally hostile. Operating successfully under these conditions will necessitate the use of a stable hull design with a high endurance and the ability to operate independent of support assets due to the nature of the BMD mission. The following is a description of the platform component in moderate detail.

Hull, Mechanical and Electrical (HM&E) components of the platform need to support lengthy on-station periods. The sea frame must be a stable sea keeping platform. It must effectively operate in seas up to and including Sea State 5: 30 knots sustained winds and 18-foot seas. This is based upon mission requirements for continuous on-station operations in adverse weather conditions.[44] Sea keeping is a factor in real-world, sea-based BMD operations, with ships occasionally leaving assigned patrol stations and proceeding to port due to heavy weather. The platform must be capable of 30 days of on station operations (not replenished), and up to 90 days of on-station operations if supply assets are available, again, based on mission requirements for operating independently for extended periods. It must interface with all existing Underway Replenishment (UNREP) systems and rigs, both United States and allied. This encompasses rigs for petroleum products, fresh water, cargo, and ammunition.

High speed capability will be needed for transit to and from the designated patrol region (25 kts sustained). The vessel will require an unreplenished cruising range of 5,000 nautical miles (NM) at 16 kts,[45] with a low fuel-consumption capability for loitering in patrol region for extended periods of time. Bow and Stern thrusters will be installed to permit maximum lateral maneuvering capability, permitting maximum flexibility in harbor maneuvering situations, and alleviating some need for the use of harbor tugs, a significant issue if a short-notice sortie is necessary. Overall draft will not exceed 20 feet (approximately 7 meters). This permits entry into a greater number of ports worldwide for resupply and pier-side maintenance. Sufficient Ship's-Service Generator capacity to produce a power output supporting continuous high-power

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[44] http://en.wikipedia.org/wiki/Sea_State

[45] http://www.naval-technology.com/projects/ticonderoga/

operation of radars, communications, environmental and propulsion systems will also be essential. Also, the excessive power consumption of some proposed BMD interceptors, such as DEWs and railguns, must be accommodated.

Like all frontline U.S. Naval warships, aircraft and small-boat facilities are needed for defensive measures, collateral duties, and in this case, for the support and completion of the overall mission of successful BM interception. Such facilities will include being capable of embarking one helicopter of at least MH-60R/MH-60S size, weight, and dimension with a hangar facility for maintenance and storage. A flight deck of sufficient size and weight will be needed to land at up to one MH-53E or one MV-22 aircraft, to support long range Vertical On-board Delivery (VOD). Furthermore, facilities and provisions for at least two embarked small boats, nominally one 11-meter RHIB and one 7-meter RHIB are necessary to be used for Force Protection, Search and Rescue, and personnel transfer.

For self-defense weaponry, a variety of weapon systems should be considered. For short-range Anti-Surface and Anti-Air defense, one deck gun similar in performance to the MK-45 series 5-inch (127 mm) weapon system should be included. Additionally, a short-range missile system to defend against hostile aircraft, missiles, and small surface craft is necessary. For close-in defense, a Block 1 B Phalanx Close In Weapon System (CIWS) with infrared tracking and antisurface capability,[46] or a successive system of similar specifications, for close-in antimissile defense and deterrence of the small boat/low-slow aircraft threat.

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[46] http://www.fas.org/man/dod-101/sys/ship/weaps/mk-15.htm

To satisfy the force protection mission, the design should include installation of an optical surveillance system to support Anti-Terrorism/Force Protection (AT/FP) measures (including multiple remote-controlled, heavy caliber machine guns), and a rudimentary Anti-Submarine Warfare (ASW) suite for self-defense (including two torpedo decoys, a hull-mounted passive detection sonar system, and fire control systems to support Vertically Launched ASROC (VLA)), for self-defense purposes. Various smaller personal and crew-served weapons for contingency operations such as boarding and force protection will be needed.

Crew complement should not to exceed that of a TICONDEROGA-class cruiser.[47] Ship's company: 24 officers, 340 enlisted; Helicopter Detachment: 6 officers, 25 enlisted, with an additional provision for overflow capability: 6 officer berths, 30 enlisted berths.

The vessel will also field a Vertical Launching System (VLS), nominally matching the design capabilities of the MK-57 VLS, developed for the DDG-1000 program. A minimum of 60 cells will be embarked, to support the deployment of self-defense missiles (the ESSM) and rocket-thrown torpedoes (the VLA), with an open architecture capable of supporting larger and heavier weapons of future designs.

5.3.1 Performance Analysis of Shipborne Radar Systems

5.3.1.1 Radar Background

WMDs, and the BMs that deliver them, pose a major threat to the security of the United States and its allies. A vital component of the strategy is the ability to perform long-range surveillance and tracking of the TBMs upon initial launch. A key element in the overall Sensor Architecture for BMD is the radar system. Radar provides

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[47] http://www.globalsecurity.org/military/systems/ship/cg-47.htm

around-the-clock, all-weather surveillance and tracking of BM threats with extremely accurate range, azimuth, elevation, and velocity (Doppler) measurements. Onboard shipborne radar systems, in particular, can perform:

- 24/7, all around surveillance and early warning detection of BM launch;
- target acquisition and continuous accurate tracking of the missile threat throughout its trajectory;
- guidance of interceptor in-flight from launch until the Kill Vehicle autonomously acquires the target for the engagement; and
- BDA of the engagement.

As such, performance analysis of onboard shipborne radar systems for BMD is an important and integral part of designing robust and effective BMD solutions.

5.3.1.2 Radar Objectives

The objectives are:

- Analyze the detection performances of two types of onboard shipborne radar systems; namely, the upgraded SPY-1B radar and the Conformal aperstructure phased array radar that exploits the entire ship's structure as a radar aperture.
- Specify detection ranges of the two types of onboard shipborne radar systems against BMs as inputs for further system-level architecture modeling.

5.3.1.3 Surveillance Radar Equation and Range Prediction for the Upgraded SPY-1B

The theoretical maximum detection range (R_{max}), for a radar operating in surveillance mode, can be predicted using the radar range equations discussed in Merrill Skolnik's book, *Introduction to Radar Systems*.[48] These equations account for many, but not all, of the factors that influence the detection performance of a noise-limited radar system. The surveillance radar range equation is given as

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[48] Merrill I. Skolnik, *Introduction to Radar Systems*, McGraw-Hill, 3rd Ed., 2001.

$$R_{\max}^{4} = \frac{P_{ave} A_e \sigma \varepsilon_i(n)}{4\pi k T_o F_n (S/N)_1 L_s} \times \frac{t_s}{\Omega},$$

where

$R_{\max}$ = Maximum radar range or detection range [m]

P_{ave} = Average transmitted power [W]

A_e = Antenna effective aperture [m^2]

σ = Radar cross-section of target [m^2]

n = Number of pulses integrated

$\varepsilon_1(n)$ = Integration efficiency

k = Boltzmann's constant = 1.38×10^{-23} [J/degree]

T_0 = Standard temperature = 290 [K]

F_n = Receiver noise figure

$(S/N)_1$ = Signal-to-noise ratio (SNR) required for detection based on a single pulse

L = System loss

t_s = Time required to scan a solid angle, Ω [sec]

Thus, the surveillance radar detection capability is largely dependent on the average power and the effective aperture; collectively known as the power-aperture product and the time required to scan one steradian in solid angle.

The solid angle, (Ω) is determined by the azimuth to be scanned and the elevation of the scanned sector. The scan time, t_s, is equal to $t_0\Omega/\Omega_0$, where $t_0 = n/f_p$ is the time that the radar beam dwells on the target, n is the number of pulses integrated for detection in surveillance mode, f_p is the radar pulse repetition frequency and Ω_0 is the solid angle of the radar main-lobe beam.

5.3.1.4 Computation of Integration Efficiency, $\varepsilon_I(N)$ and Improvement Factor, I(N)

The integration efficiency for noncoherent integration may be defined as

$$\varepsilon_i(n) = \frac{S/N_1}{n(S/N)_n},$$

where $(S/N)_n$ is the required signal-to-noise ratio per pulse when n pulses are integrated.

The corresponding improvement in signal-to-noise ratio when n pulses are integrated is called the integration improvement factor, $I(n) = n\varepsilon_i(n)$ and can be derived empirically[49] as

$$\left[I(n)\right]_{dB} = 6.79\left(1+0.235P_d\right)\left(1+\frac{\log\left(1/P_{fa}\right)}{46.6}\right)\log(n)\left(1-0.140\log(n)+0.018310(\log n)^2\right).$$

A plot of improvement factor, $I(n)$ verses the number of pulses (noncoherent integration) is shown in Figure 17 for probability of detection (Pd) of 0.5, 0.9, 0.95 and 0.999 and probability of false alarm (Pfa) of 1.0 x 10^{-2}, 1.0 x 10^{-6}, 1.0 x 10^{-10}, and 1.0 x 10^{-13}, respectively.

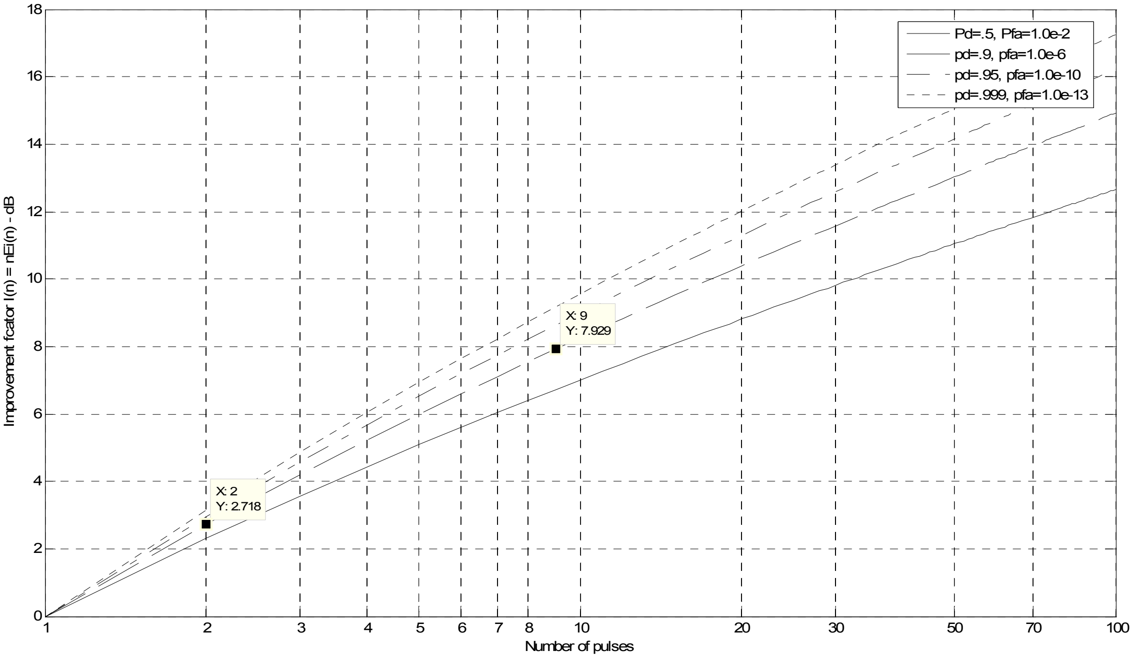

Figure 17. Plot of Improvement Factor versus the Number of Pulses Integrated

From the above plot, the improvement factor, $I(n)$ when $n = 2$ (assumed number of pulses integrated for the upgraded SPY-1B radar in surveillance mode) is 2.718dB. The corresponding integration efficiency $\varepsilon_i(n)$ is 0.93.

Similarly, the improvement factor, $I(n)$ when $n = 9$ (assumed number of pulses integrated for the upgraded SPY-1B radar in tracking mode) is 7.929dB. The corresponding integration efficiency, $\varepsilon_i(n)$ is 0.69.

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[49] P.Z. Peebles, Jr., *Radar Principles*, John Wiley & Sons, Inc., 1998.

5.3.1.5 *Computation of Single Pulse Signal-to-Noise Ratio, (SNR)$_1$ for Detection*

The SNR required for detection based on a single pulse, (*S*/*N*)$_1$ for a given probability of detection (*Pd*) and probability of false alarm (*Pfa*) can be approximated by Albersheim's empirical formula[50] given as:

$$\left[(S/N)_1\right]_{dB} = 10\log(A + 0.12B + 1.7B),$$

where $A = \ln[0.62 / Pfa]$ and $B = \ln[Pd / (1 - Pd)]$.

A plot of the single pulse detection Signal-to-Noise Ratio, (*S*/*N*)$_1$ versus the probability of detection (*Pd*) for probability of false alarm (*Pfa*) of 1.0 x 10^{-2}, 1.0 x 10^{-6}, 1.0 x 10^{-10}, and 1.0 x 10^{-13} is shown in Figure 18.

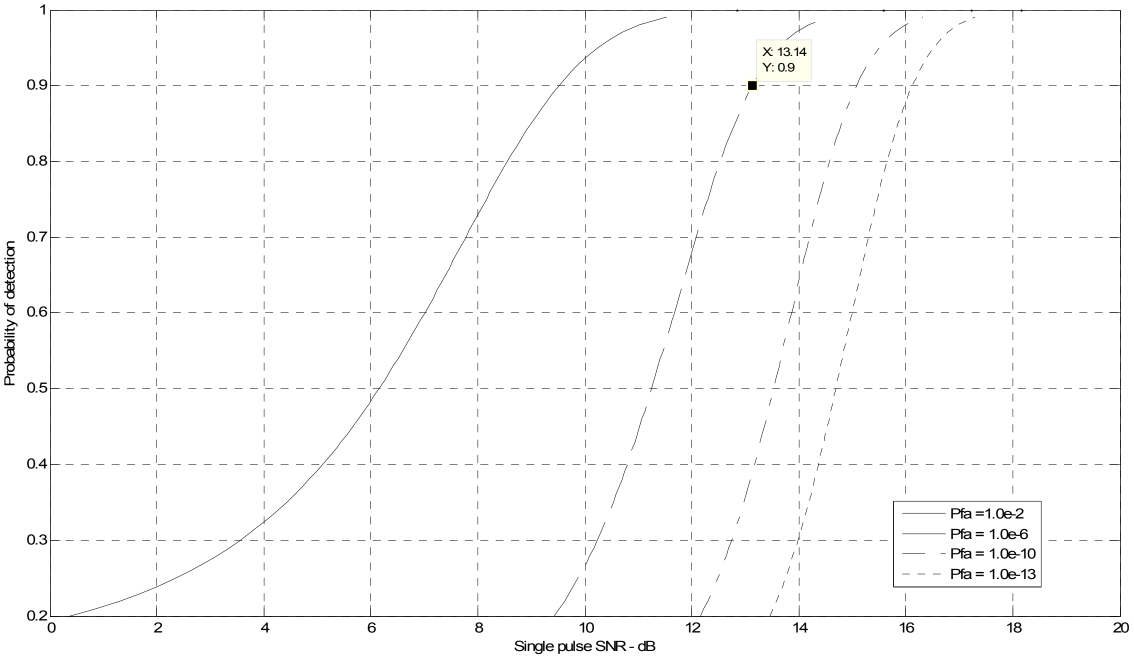

Figure 18. Plot of Probability of Detection versus Single Pulse SNR

From Figure 18, the single pulse Signal-to-Noise Ratio, (*SNR*)$_1$ required for a 90% probability of detection and a 1.0 x 10^{-6} probability of false alarm is 13.14dB. The cumulative detection probability is 0.99 for two scan (assumed requirements for the upgraded SPY-1B radar).

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[50] W.J. Albersheim, "A Closed-Form Approximation to Robertson's Detection Characteristics," Proceedings IEEE 69, July 1981, p. 839.

5.3.1.6 Computation of Minimum Signal-to-Noise Ratio, $(SNR)_{min}$

The minimum signal-to-noise ratio, $(SNR)_{min}$ required is given by,

$$(SNR)_{\min} = \frac{(S/N)_1}{\varepsilon_i(n)} .$$

The corresponding $(SNR)_{min}$ required by the upgraded SPY-1B radar for a single scan probability of detection of 0.9 and probability of false alarm of 1.0 x 10^{-6} are 13.4dB for surveillance mode and 14.8dB for tracking mode.

5.3.1.7 Radar Parameters

The upgraded SPY-1B radar is intended to have an increased power-aperture product of about 70% using the same 3.85m by 3.65m physical antenna aperture. The assumed radar parameters are tabulated in Table 3.

Radar Parameters	Upgraded SPY 1B Radar
Operating frequency (GHz)	3.3
Pulse repetition frequency (Hz)	17
Total average power (kW)	100
Antenna height (m)	3.85
Antenna width (m)	3.65
Physical aperture (m^2)	14.1
Effective aperture (m^2)	12.0
Power-aperture product (dB)	60.8
Receiving gain (with weighting) (dB)	42.6
Weighted azimuth beamwidth (deg)	1.6
Weighted elevation beamwidth (deg)	1.52
Azimuth scan sector (deg)	90
Search solid angle (sr)	0.0415
Beam solid angle (sr)	$7.38\text{x}10^{-4}$
Noise temperature (K)	500
Noise figure (dB)	3.2
System and atmospheric losses (dB)	18.4
Surveillance scan time (sec)	6.6
Pulses integrated for surveillance	2
Track integration time (sec)	0.53
Pulses integrated for tracking	9

Table 3. Estimated Radar Parameters for the Upgraded SPY-1B Radar

Many of the above parameters used for the computation of range performance come from the American Physical Society (APS) study.[51]

5.3.1.8 Computation of Radar Range Performance in Surveillance Mode

Using the radar parameters listed in Table 3, the radar range performance in surveillance mode against a 0.5m^2 BM is computed using the MATLAB codes[52] to have a maximum detection range of 722 km given a power-aperture product of 60.8dB as shown in Figure 19.

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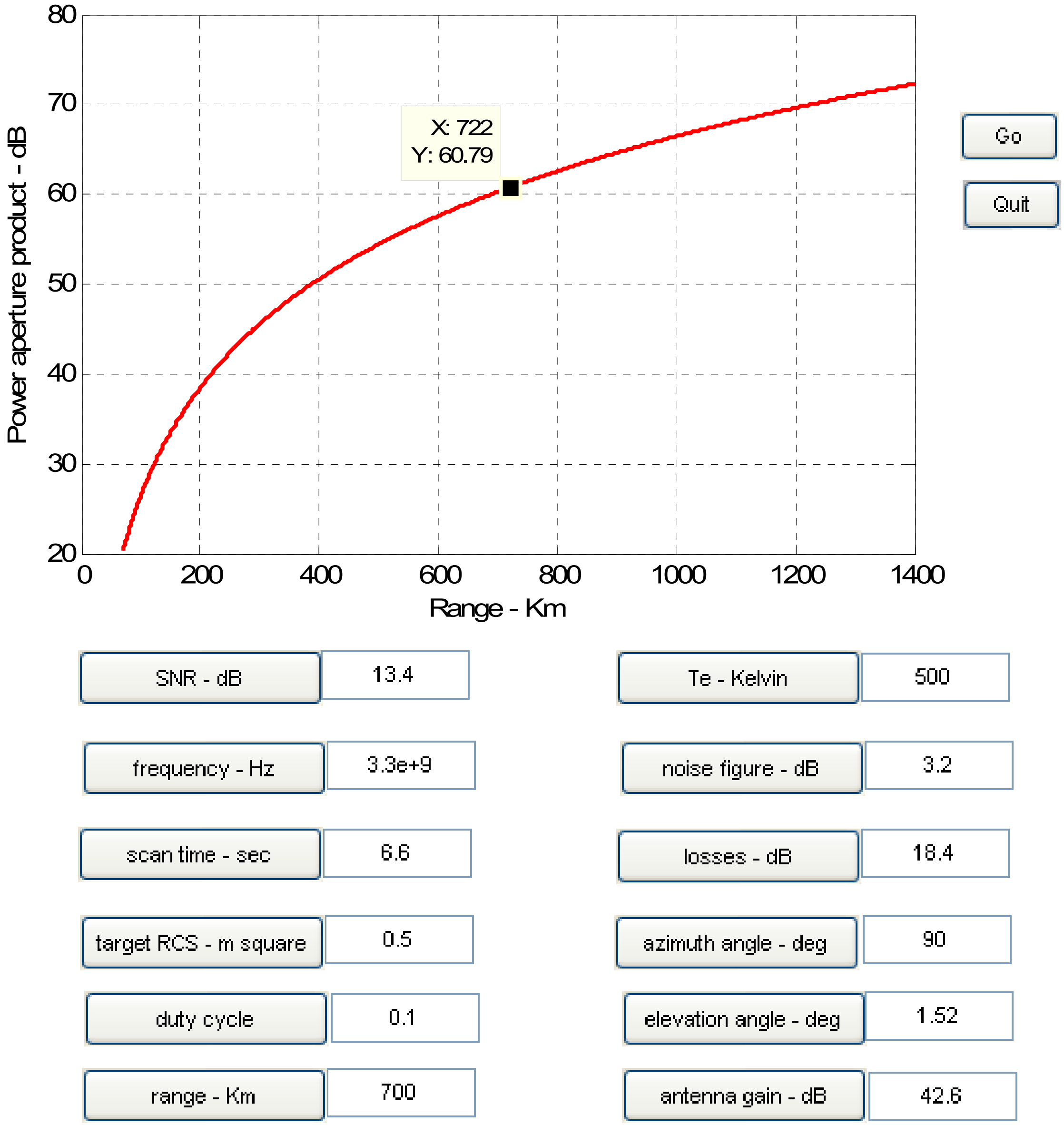
[51] APS Study, "Boost-Phase Intercept Systems for National Missile Defense," July 2003, Sections 10.2.3-10.2.5.

[52] Bassem R. Mahafza, *Radar Analysis and Design Using MATLAB*, Chapman & Hall/CRC, 2000.



SNR - dB: 13.4
frequency - Hz: 3.3e+9
scan time - sec: 6.6
target RCS - m square: 0.5
duty cycle: 0.1
range - Km: 700
Te - Kelvin: 500
noise figure - dB: 3.2
losses - dB: 18.4
azimuth angle - deg: 90
elevation angle - deg: 1.52
antenna gain - dB: 42.6

Figure 19. GUI and Plot for the Computation of Radar Performance in Surveillance Mode

5.3.1.9 Computation of Radar Range Performance in Tracking Mode

Similarly, the radar range performance in tracking mode (when SPY radar is cued by an early warning radar) against a $0.5m^2$ BM, can be computed using the radar parameters listed in Table 3 and MATLAB codes.[53] The maximum detection range is

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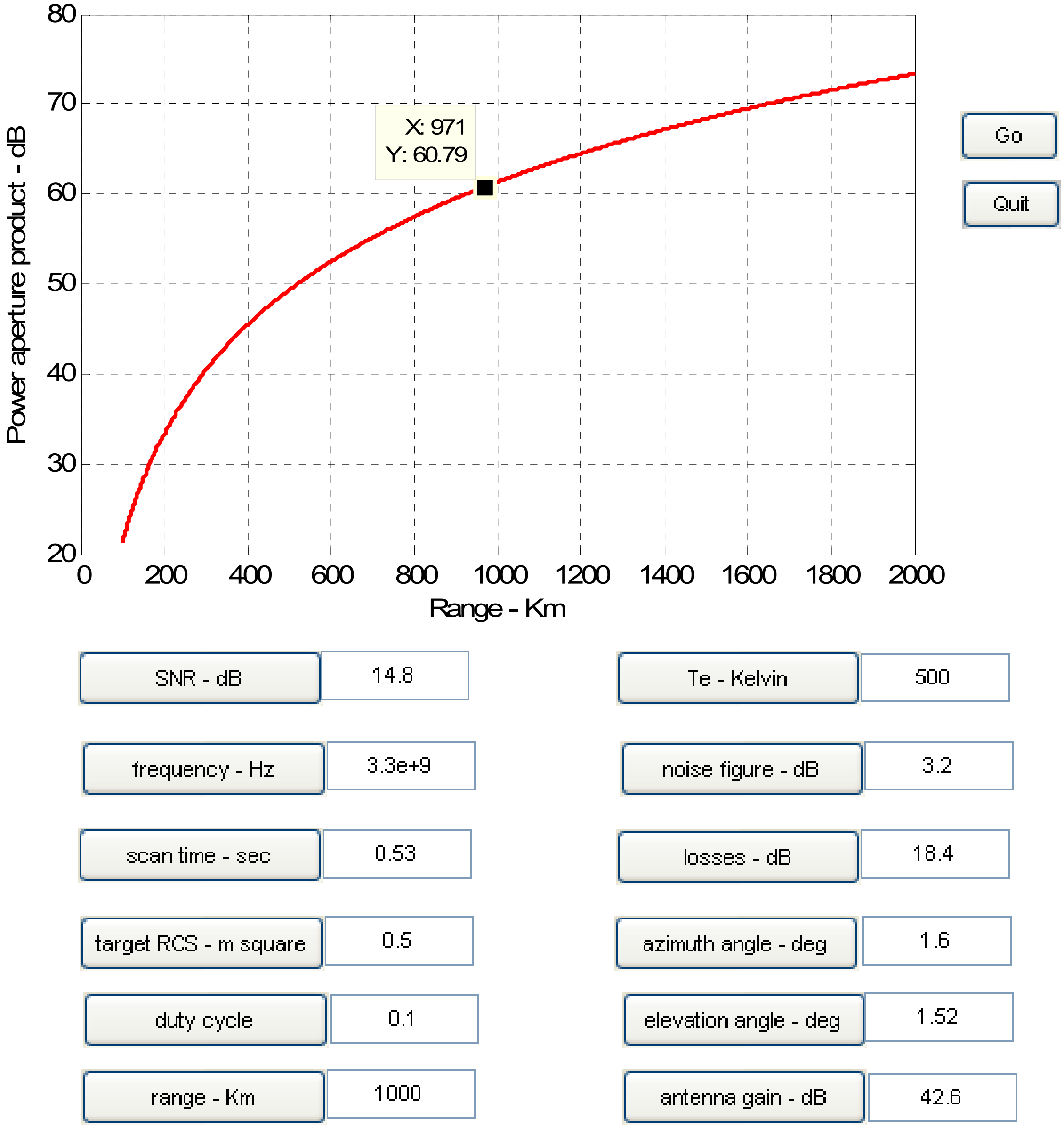
[53] Bassem R. Mahafza, *Radar Analysis and Design Using MATLAB*, Chapman & Hall/CRC, 2000.

computed to be 971 km given a power-aperture product of 60.8dB as shown in Figure 20.



SNR - dB	14.8	Te - Kelvin	500
frequency - Hz	3.3e+9	noise figure - dB	3.2
scan time - sec	0.53	losses - dB	18.4
target RCS - m square	0.5	azimuth angle - deg	1.6
duty cycle	0.1	elevation angle - deg	1.52
range - Km	1000	antenna gain - dB	42.6

Figure 20. GUI and Plot for the Computation of Radar Performance in Tracking Mode

5.3.1.10 Phased Array Surveillance Radar (PASR) and Skin-of-the-Ship (SOTS) Radar

A vital component of the BMD strategy is the ability to perform long-range surveillance and tracking of the BMs upon initial launch. Navy ships that perform this role are equipped with conventional, large, phased array radars with thousands of independent, active array elements to detect and discriminate missile targets from thousands of miles away. Clearly the volume and weight of such an array is undesirable, especially if it is to be mounted on a ship for forward deployment. Thus, new antenna concepts and technologies have been studied and dramatic performance improvements can be made to the PASR.

The "opportunistic array" concept[54] has been the focus of research and development undertaken by the Naval Postgraduate School (NPS). An opportunistic array is an integrated, ship-wide, digital, phased array, where the array elements are placed at available open areas over the entire surface of the platform. The elements of the opportunistic array are self-standing, digital, transmit/receive (T/R) modules with no hardwire connections other than prime power. Element localization and synchronization signals, beam control data, and digitized target return signals are passed wirelessly between the elements and a central signal processor.

The opportunistic array concept and its digital architecture also complement the "aperstructures" philosophy, where the array is an integrated load-bearing part of the ship structure. The aperstructure concept aims to exploit the entire ship's structure as a radar aperture and employ individual antenna elements that are conformal and integrated into the ship's structure. The opportunistic array concept and aperstructure concept can be synergized into a SOTS radar. The advantages of a SOTS radar are:

High Angular Resolution

The primary advantage of the SOTS radar is the high angular resolution that can be achieved by utilizing the entire ship's structure as an aperture.

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[54] Yong Loke, "Sensor Synchronization, Geolocation and Wireless Communication in A Shipboard Opportunistic Array," Master's Thesis, Naval Postgraduate School, Monterey, CA, March 2006.

Enhanced Stealth

Low profile patch antennas, integrated into the ship's structure using hull appliqués, hold the key to minimizing the ship's visual and infrared signatures, and its radar cross section.

Multifunction

The digital architecture of the SOTS radar offers several advantages over conventional radar designs. Advanced signal processing techniques, coupled with broadband patch antenna designs, offer the possibility of integrating radar, direction finding, and satellite communications functions into the array. The result is a single aperstructure replacing the numerous antennas and masts populating the superstructures of present-day ships.

Increased Survivability and Operational Availability

The SOTS array is inherently more survivable and has increased operational availability vis-à-vis conventional radars. A radar architecture, with hundreds of dispersed antenna elements ensures that operations will continue even if a number of elements, are disabled (due to enemy action or maintenance requirements). The modularity and accessibility of the antenna elements also means that damaged elements can be quickly replaced, even if the ship is on the high seas. In addition, the relationship between the performance of the radar and the number of functioning elements can be well-predicted, allowing any degradation in radar performance to be compensated by tactical means.

The radar's theoretical maximum range was given by

$$R_{\max}^4 = \frac{P_{ave} G A_e \sigma n \varepsilon_i(n)}{(4\pi)^2 k T_o F_n (B_n \tau)(S/N)_1 f_p},$$

where the additional terms are

B_n = Receiver noise bandwidth [Hz]

τ = Pulse width [m]

f_p = Pulse repetition frequency [Hz].

Using the values of gain determined for various numbers of elements, the relationship between the theoretical maximum range and the total number of antenna elements can be determined.[55] Figure 21 shows this relationship for N = 400, 800, and 1,200. Assuming that each element delivers an average power of approximately 500 W, only 400 elements are required to achieve a theoretical maximum range of 1,000 km. If 800 elements are available, a theoretical maximum range of approximately 1,600 km is possible. If 1,200 elements are available, a theoretical maximum range beyond 2,000 km is possible.

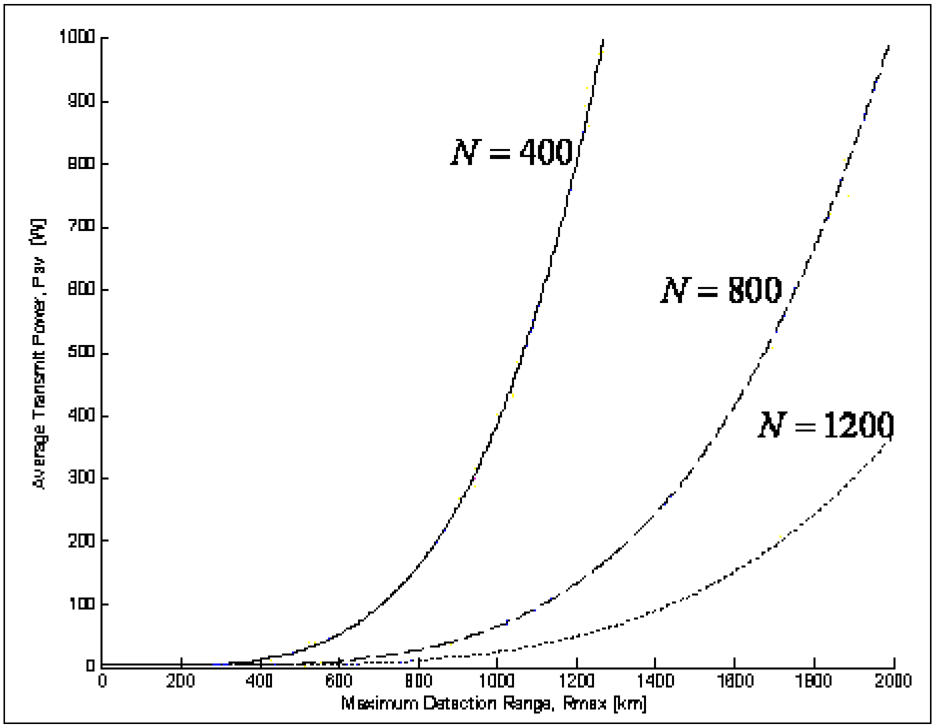

Figure 21. SOTS Radar Performance for Different Number of Elements

5.4 INTERCEPTORS

To counter the threat of a BM that threatens to destroy strategic, operational, and/or tactical points of interest, an interceptor weapon must be employed to negate the threat of the BM. To negate the BM threat, several technologies were investigated to determine their respective feasibility as an anti-ballistic missile interceptor. The interceptor technologies investigated during the course of project SABR fall into three major categories: missiles, directed energy, and railgun. Within these categories several alternatives were explored and those deemed feasible as a BM interceptor were carried

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[55] Tong M. Chin Hong, “System Study and Design of Broadband U-Slot Microstrip Patch Antennas for Aperstructures and Opportunistic Arrays,” Naval Postgraduate School, Monterey, CA, December 2005.

forward into physical and system modeling for evaluation. The most feasible interceptor technologies were the missile, free electron laser, particle beam, and railgun.

5.4.1 Missile

The airframe body and control deflection surfaces of the missile generate the bulk of the maneuver capability to steer the missile for interception towards the target. Thus airframe maneuverability is a crucial design specification and evaluative parameter to assess the performance of the missile.

5.4.1.1 Classes of Missiles

Most missiles may be classified into four general classes: AAM, SAM, ASM, and SSM, of which only the AAM and SAM will be discussed.

The air-to-air missile (AAM), as the name implies, is one which is launched in the air against another flying aircraft or air target. The AAM is generally of the smaller variant due to carriage limitation and is typically short range in nature. However, the maneuverability requirement for this class of missile is most severe in comparison with other classes of missiles, mainly due to relatively high launch velocity, high target velocity and maneuverability and relative short flight time for flight path corrections. In addition, the wide range of operating altitude imposed steep design challenges for the missile deflection control, as the missile is expected to meet both the low altitude and high altitude control requirement, which are diametrically different in nature, due to variation of atmosphere with height.

The surface-to-air missile (SAM) is designed for area defense against attacking aircraft or BMs. As such, the aerodynamic design depends on its range, which varies from a few miles to several hundred miles. The maneuverability requirement for this class of missile can be quite severe, especially against low, fast-flying targets.[56]

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[56] S.S. Chin, *Missile Configuration Design*: *General Aerodynamic Design Considerations*, McGraw-Hill Book Company, Inc., New York, 1961, p. 4-12.

5.4.1.2 Types of Design and Control

In general, there are many types of aerodynamic control configurations (and modifications thereof) employed for the four classes of missiles.

Wing Control

The wing control configuration consists of a relatively large wing located close to the missile's center of gravity (CG) and a set of tail or stabilizing surfaces at the aft end of the missile. Because the wing deflection generates instantaneous lift for maneuvering flight, the response is very fast, and additional lift is generated as the angle of attack (AOA) builds up. However, control effectiveness $C_{m\delta}$ (pitching or turning moment due to control surface deflection) from the wing is generally small due to the wing proximity to the CG of the missile. The resulting downwash has a beneficial effect on the tails as it generates a download that provides the desired turning moment to develop AOA for additional lift. The position of a wing for a wing control design is crucial, as the CG of a missile will change during flight due to the rocket fuel being expended. The trimmed AOA value is usually small for wing control design, and this is advantageous for inlet design of air breathing power-plant and guidance seeker designs.

Canard Control

A canard control configuration consists of a set of small control surfaces located well forward on the body and a set of large surfaces (wing or tail) attached to the middle or aft section of the missile. Canard downwash is less significant compared to wing control; as such, the longitudinal stability is affected less adversely, which implies that large static margins can be obtained by simple variation in wing location. Advantages of canard are its inherent simplicity due to the small size in control system and its location in the nose. The total drag and weight of the missile are also reduced, as the total lifting surface area is lower. Disadvantages of canard control are: (1) roll stabilization is difficult with the use of canard, hence a more complex method of roll control is required; and (2) relatively large control surface rate is required to obtain the desired rate of response, since the AOA must be generated before lift is developed. Application is most suited for relatively small missiles that do not require roll attitude stabilization.

Tail Control

As the name implies, the control deflection comes from the tail, thus the deflection must be opposite in direction to the AOA, which results in relatively slow response. Advantage of tail control is tail load and hinge moments are kept relatively low as the total local AOA on the tail is reduced, which reduces the body bending to a minimum; moreover, the aerodynamic characteristics are more linear than wing control design. Disadvantages are: (1) limited tail estate to house the control mechanism if solid rocket motor is employed; and (2) deficiency of tail surfaces to provide desired lateral control.

Tail-less Control

Tail-less (or wing control) involves one set of surfaces (wing) with control flaps located at the trailing edge. An advantage is the reduced number of surfaces, which results in reduced drag and manufacturing costs. A disadvantage is that the control effectiveness and aerodynamic damping is extremely sensitive to the location of the wing.

Base Extension

Base extensions exploit the use of pressure differential between the base and the free stream. A segment is extended aft of the body into the region of differential pressure to generate lift force for control. Advantages are: (1) low servo power requirement due to absence of hinge moment; and (2) simplicity and compact in design. Disadvantages are: (1) low maneuverability; (2) inoperability at subsonic speeds; and (3) reversal in control between power-on and power-off conditions due to jet effects.

Nose Flap Control

Nose flap control is composed of a segment of the nose or flap extended from each of the four quadrants. An advantage is the compact design when used with extremely low aspect ratio tail surfaces. A disadvantage is low maneuverability.

Dorsal Control

Dorsal control employed in certain applications where overall span of the missile is limited, and is considered as an “aerodynamic fix” to make up for the loss in aerodynamic efficiency due to reduction in tail aspect ratio and/or area.

Jet Control

Jet Control is comprised of four classes: (1) simple auxiliary jet (rocket) reactions; (2) gimbaled engine and/or rocket nozzles; (3) jet vanes; and (4) jetavators.

1. Simple jet reaction can be used to provide stabilization or spin (rolling velocity) to minimize dispersion in free flight, especially for short-range missiles, and provide jet or air injection augmentation of aerodynamic surfaces.
2. Gimbaled engines can be used to control the flight path of the missile during phases of flight where aerodynamic control is inadequate, such as during liftoff where dynamic pressure is low, or at extremely high altitudes where air density is low.
3. Jet vanes are used to provide or supplement aerodynamic controls. A major challenge is to develop a material to withstand the high temperature for a prolonged operating period.
4. Jetavators are novel devices that change the direction of the jet flow for thrust vector control; it requires relatively low operating forces because of its low hinge moment.

5.4.1.3 Maneuverability and Static Stability

The maneuverability of a missile is examined using the load factor sensitivity (LFS) equation, which is related to the missile derivatives as:

$$\frac{\Delta n}{\Delta \delta} = \left(C_{N\delta} - \frac{C_{N\alpha} C_{M\delta}}{C_{M\alpha}} \right) \frac{\bar{q}\, S}{W},$$

where Δn is the change in load factor of the missile

$\Delta\delta$ is the change in deflection angle

$C_{N\delta}$ is the lift coefficient derivative with respect to deflection angle, δ

$C_{N\alpha}$ is the lift coefficient derivative with respect to AOA, α

$C_{M\delta}$ is the moment coefficient derivative with respect to deflection angle, δ

$C_{M\alpha}$ is the moment coefficient derivative with respect to AOA, α

$\bar{q}$ is the dynamic pressure, S is the reference area, W is the weight of the missile.

From static stability study of the missile, the static margin normalized with missile diameter is $\frac{\bar{x}}{d}$, where the distance between the missile neutral point and its CG is $\bar{x}$. Using the relationship between static margin and missile derivatives, the LFS equation can be reexpressed by the equation:

$$\frac{\bar{x}}{d} = \frac{C_{M\alpha}}{C_{N\alpha}}$$

$$\frac{\Delta n}{\Delta \delta} = \left(C_{N\delta} - \frac{C_{M\delta}}{\frac{C_{M\alpha}}{C_{N\alpha}}} \right) \frac{\bar{q}\,S}{W} = \left(C_{N\delta} - \frac{C_{M\delta}}{\frac{\bar{x}}{d}} \right) \frac{\bar{q}\,S}{W}.$$

For tail control, $C_{N\delta}$ is a small positive quantity, $C_{M\delta}$ is a negative quantity, and $\frac{\bar{x}}{d}$ is also a negative quantity for positive static stability (neutral point behind CG).

From the LFS expression, requirements for large static stability margin and great load factor or maneuvering capability are conflicting, in that increasing the stability margin results in a decrease in load factor capability. As the missile burns off its fuel in flight, the CG moves forward, the static margin increases, the maneuverability of the missile correspondingly reduces; a multistage rocket launch is one strategy that is employed to overcome the maneuverability problem by segmenting the control problem into a progressively smaller segment of the missile entity, by actively balancing the maneuverability and static stability requirements of the missile throughout the flight regime.[57]

5.4.2 Directed Energy Weapons (DEWs)

DEWs have key attributes that lend themselves as highly sought after weapons for current and future development. DEWs are capable of engaging targets in a near

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[57] Class Notes, ME3205, Maneuverability vs. Static Stability, Naval Postgraduate School, Monterey, CA, pp. 23-24.

speed-of-light engagement, enabling the engagement of highly maneuverable, crossing, and/or extremely fast targets. Since now there is an actual munition fired, the potential for a bottomless magazine exists. The deep magazines of a DEW system will enable far more engagements than current missile systems allow. Not firing a physical round, there is also a minimization of collateral damage, since there are not booster, air-frame, and warhead fragments to deal with from the interceptor weapon.

DEWs use highly correlated, intensified and directional energy beam in the megawatts class as the kill mechanism. The energy, power, intensity, and threshold of the system are generally determined by the technology in which energy is generated. The technologies under consideration are lasers and particle beams.

5.4.2.1 Lasers

Laser pumping is the generation of energy by stimulated emission of radiation through the excitation of low energy photons to high energy state and amplification through a gain medium. Electrical or optical laser pumping occurs in several forms and is dependent on the gain medium and the end state power intensity required. While the physics of laser emission do not change, the means of laser pumping does and are generally found in the following classes:

- Solid state laser
- Gas laser
- Chemical laser
- Free electron laser

The advantages of employing a high power tactical laser system are:

- speed of light delivery of high power destruction beam onto desired target;
- deep magazine as the energy required to propel laser is basically electrical power;
- minimal collateral damage given precision beam tracking and firing;
- multiple target engagements and rapid retargeting with electronic steering;
- and low logistic support requirement and operational cost.

This list not all inclusive, but outlines prime factors considered beneficial when employing a laser as the primary tactical system.

5.4.2.2 Laser Technical Challenges

Lasers suffer losses that limit applications considered critical to military operations. It is therefore favorable to study the feasibility of the different systems available to determine the most viable system with the ability to fulfill essential tactical requirements.

A typical laser system generally consists of several essential components: a gain medium for emission, a lasing pump, a resonator cavity, thermal cooling, and waveguide systems.

The primary source of loss in a laser's effectiveness is the attenuation loss due to the atmospheric conditions experienced by the system. Beam divergence at a distance where power loss becomes undesirable, can be determined by the equation $w(z) = w_o\left[1+\left(\lambda z/\pi.w_o^{2}\right)^{2}\right]^{1/2}$, where w(z) = beam width at distance z, z = distance from emission origin, w_o = minimum beam waist at origin, and λ = wavelength. Other atmospheric effects critical to laser operations include blooming, absorption, and scattering.

Solid State Laser

A solid state laser uses solid material such as glass, ruby, neodymium YAG, etc. as the gain medium and optical pumping via flash lamp. The beam wavelength emitted by a solid state laser varies from near infrared (0.5 micrometers) to mid infra red region (3 micrometers) and is dictated by the gain medium used. This class of laser is potentially very efficient and high power generation in the kilowatt class is achievable through use of a different gain medium. Nevertheless, cooling and waste heat removal in a high power generation system is not trivial.

Distortion of the laser medium and reflective mirror becomes prominent when the system is subjected to prolonged operational duration. As such, high power, solid state lasers are limited by noncontinuous operation where short pulses, followed by cooling down, are required. Moreover, existing solid state technology with low powered flash lamp or diode requires development of a high power, high efficiency, and low cost laser pump in order to be feasible for military engagement. This, in conjunction with the fixed frequency output, eliminated the solid state laser from further consideration.[58]

Gas Laser

Gas lasers, inherently powered by a electrical pumping and reaction of gases such as argon, helium-neon, and other combinations, are capable of producing power in the kilowatts class and wavelength at the near infrared spectrum. Nevertheless, operation of this class of laser as a tactical weapon is not desirable, as large amounts of reactant gas would be required to boost the kilowatt system to a megawatt class. Moreover, the gas dynamic varies with operating conditions and produces a beam at an unfavorable wavelength for propagation and is susceptible to atmospheric attenuation, which is not desirable for military operation. These factors, combined with the space available onboard a ship's platform, eliminated the gas laser from further consideration.

Chemical Laser

Chemical lasers are powered by a chemical reaction from a combination of chemical compounds. An example would be the Chemical Oxygen Iodine Laser (COIL) employed by the U.S. Air Force, which uses gaseous chlorine, molecular iodine, and an aqueous mixture of hydrogen peroxide and potassium hydroxide for laser generation. The COIL is a megawatt-class laser operating in the midinfrared region and is optimal for operation in atmospheric conditions with minimal attenuation. However, there is still the need to overcome atmospheric attenuation imposed by a variable environment, which simply cannot be met by a single frequency laser. The employment of a chemical laser on a ship's platform raises another concern. The chemicals required in the generation of laser power pose serious hazards in storage, handling, and disposal. Based on the single frequency capability and the highly hazardous nature of the chemicals used, the chemical laser was eliminated from further consideration.[59]

Free Electron Laser (FEL)

An FEL seems promising. An accelerated relativistic electron beam acts as the lasing medium, exhibiting tunable, high power coherent radiation in wavelength

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[58] Aristeidis Kalfoutzos, "Free Electron and Solid State Lasers Development for Naval Directed Energy," Master's Thesis, Naval Postgraduate School, Monterey, CA, December 2002.

[59] Mun Kit Chan, "Atmospheric Transmission Windows for High Energy Short Pulse Lasers," Master's Thesis, Naval Postgraduate School, Monterey, CA, December 2003.

from millimeter wavelength to visible light wavelength is highly desirable to overcome atmospheric attenuation. An FEL beam is generated by accelerating a beam of electrons to relativistic speeds through an optical (vacuum) cavity with array of magnets arranged in alternating poles along the beam path, creating a periodic, transverse, sinusoidal, magnetic field, Figure 22. Acceleration of the electrons along this path results in the release of a photon. The released photons are subsequently captured by a resonator mirror to generate resonant gain. Operation in a wide range of wavelengths can be achieved by adjusting either the beam energy (speed/energy of the electrons) or the magnetic field strength. An FEL is therefore tunable to operate at various wavelengths, resulting in minimal beam distortion and atmospheric attenuation.[60, 61]

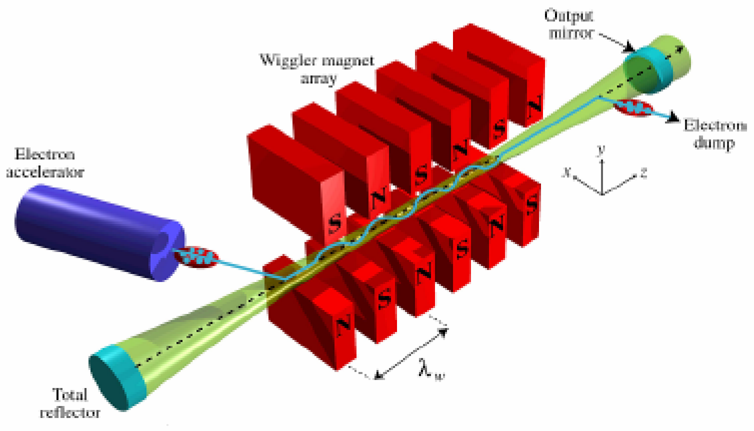

Figure 22. Electron Path Through Undulator and Optical Cavity.[62]

The FEL system, coupled with electronic beam steering, is capable of delivering a highly agile, relativistic beam with rapid-aim capabilities to meet operational requirements for moving targets, multiple targets, redeployment, and engagement.

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[60] Ivan Ng, "A Free Electron Laser Weapon for Sea Archer," Master's Thesis, Naval Postgraduate School, Monterey, CA, December 2001.

[61] Aristeidis Kalfoutzos, "Free Electron and Solid State Lasers Development for Naval Directed Energy," Master's Thesis, Naval Postgraduate School, Monterey, CA, December 2002.

[62] Robert E. Williams, "Naval Electric Weapons: The Electromagnetic Railgun and Free Electron Laser," Master's Thesis, Naval Postgraduate School, Monterey, CA, June 2004.

5.4.2.3 Particle Beam

A particle beam (Figure 23) is comprised of particles that fundamentally are positively charged photons, negatively charged electrons, or neutral atoms of hydrogen. The beam created in a particle accelerator is directed by magnets and focused by electrostatic lenses. The total energy within the beam is the aggregate energy of the rapidly moving particles, each having kinetic energy due to its own mass and motion, and is highly destructive, as accelerated subatomic particles or atoms at velocities near the speed of light are focused into the very high-energy beam. The mechanism by which a particle beam destroys a target is by depositing this high energy beam into the material of the target. As particles of the beam collide with the atomic structure of the target's material, the transfer of energy takes place and results in the target being heated rapidly to very high temperatures, causing catastrophic damages.

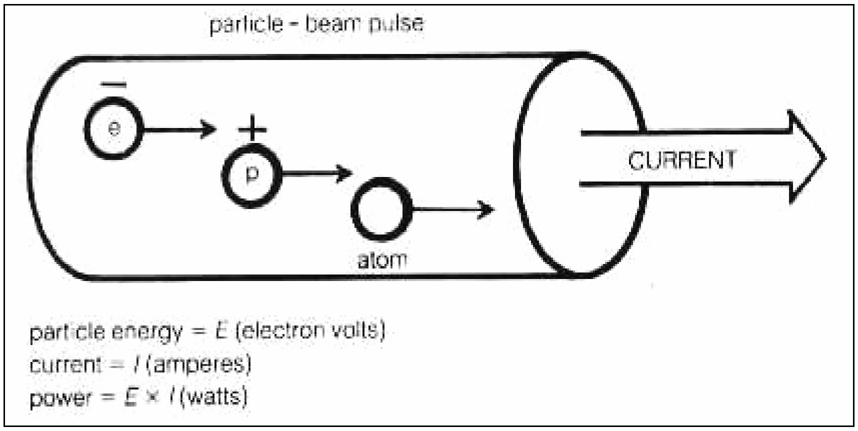

Figure 23. Working Prinicple of a Particle Beam

Broadly classified, two categories of particle beams are viable: **charged-particle beams** would be developed for use within the atmosphere (endoatmospheric) and have a set of technological characteristics that are entirely different from the **neutral particle beam** weapon that would be used in space (exoatmospheric).

An endoatmospheric system, factoring in atmospheric interference that imposes constraints that limit its use, is still an attractive option given the idealistic properties of the particle beam system. These properties, not exhaustive, include beam velocity near to speed of light, minimal beam dwell time, and beam penetration as a kill mechanism by depositing energy from the laser (Figure 24). Other capabilities of the particle beam system generally include rapid-aim-fire, all weather operability (atmospheric attenuation by scattering and absorption is not an issue critical to particle beam systems), and ancillary kill mechanism. An ancillary kill mechanism is created by the beam particles as they collide with the atoms of the air forming a cone embracing the beam and comprises many types of ionizing radiation, e.g., x-rays, neutrons, alpha and beta particles, etc. Other tertiary effects include the generation of an electromagnetic pulse (EMP) by the electric current pulse of the beam which is highly disruptive to the electronic components of the target and results in a kill by the EMP mechanism.[63] [64]

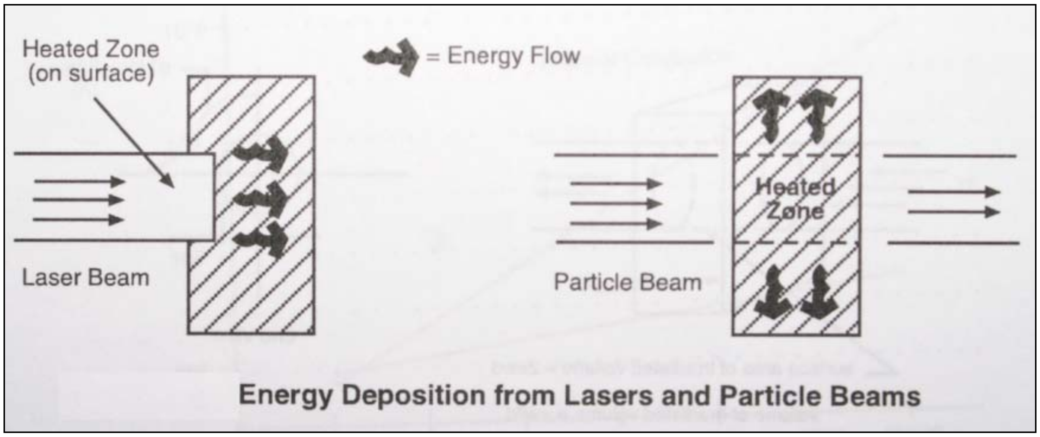

Figure 24. Energy Deposition from Lasers and Particle Beams

5.4.2.4 Directed Energy Weapons (DEWs) Conclusion

The fact that directed energy, when subjected to atmospheric attenuation, greatly reduces its capabilities and effectiveness suggests that one of the major concerns for use of directed energy in a military context involves the ability to generate high energy, megawatt class, power beams in order to be effective for military operations.

It is therefore desired that a DEW meet the following criteria:

- high energy, megawatt power beam operable in the hundreds of kilometers;

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[63] Philip E. Nielson, “Effects of Directed Energy Weapons,” 1994.

[64] Richard M. Roeberds, “Introducing the Particle Beam Weapon,” *Air University Review*, July-August 1984.

- highly tunable beam operable in a wide range of wavelengths to overcome varying atmospheric attenuation;
- multiple target engagements and rapid retargeting;
- deep magazines;
- low logistical support requirements and nonhazardous storage, handling, and disposal, if any;
- low engagement cost; and
- minimal collateral damage.

The hedge imposed by energy waste, hazardous materials, and atmospheric effects is overcome by the FEL and particle beam options and their performance was evaluated in the system model.

5.4.3 Railgun

A railgun uses electromagnetic force to propel a projectile at very high muzzle velocity. The kinetic energy imparted from the projectile to the target causes extensive damage.

In order to achieve the high muzzle velocity, the railgun utilizes an electromagnetic force called the Lorentz Force to propel an electrically conductive projectile, which initially was a part of the electromagnetic path. The current flowing through the rails sets up a magnetic field and the current through the projectile armature produces the Lorentz Force that results in the acceleration of the projectile along the rails.

5.4.3.1 Theory

A railgun consists of two parallel metal rails connected to an electrical power supply, and the circuit is complete when a conductive projectile is inserted between the rails. The electrical current runs from the positive terminal of the power supply up the positive rail, across the projectile, and down the negative rail. The flow of current makes the railgun act like an electromagnet, creating a powerful magnetic field in the region of the rails. Since the current flows in opposite directions along each rail, the net magnetic field between the rails (B) is directed vertically. In combination with the current (I) flowing across the projectile, this produces a Lorentz Force that accelerates the projectile along the rails (Figure 25).

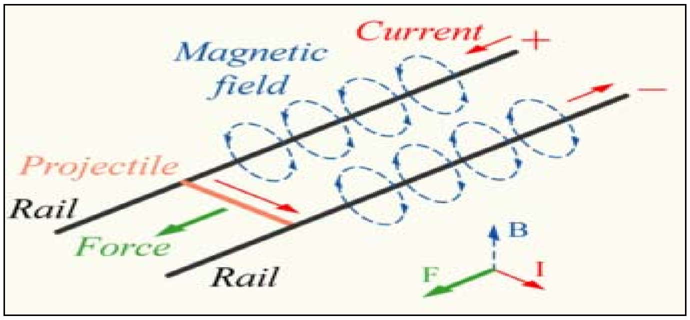


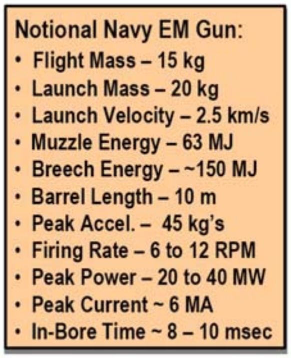
Figure 25. Schematic Diagram of the Working Principles of a Railgun (Adapted from http://en.wikipedia.org/wiki/Railgun)

5.4.3.2 Application

Current research and development shows that it is possible to use a railgun in BMD. However, this research is presently confined to the environment of the laboratory and no railgun has actually been fielded.

Recent developments in electromagnetic launcher technology in Kirkcudbright, Scotland led to a claimed speed of Mach 7.5, with a range of 370 km. In addition, the power requirement for each projectile fired was 15 ~ 30 MW and of great importance is the sustained firing rate at 6 ~ 16 rounds per minute. This allows the firing of multiple projectiles to increase overall P_H against the BM.

The requirement of the electromagnetic (EM) gun for the U.S. Navy was drawn according to the specifications and requirements of long-range fire support for ground attack, as shown in Figure 26.



Notional Navy EM Gun:

- Flight Mass – 15 kg
- Launch Mass – 20 kg
- Launch Velocity – 2.5 km/s
- Muzzle Energy – 63 MJ
- Breech Energy – ~150 MJ
- Barrel Length – 10 m
- Peak Accel. – 45 kg's
- Firing Rate – 6 to 12 RPM
- Peak Power – 20 to 40 MW
- Peak Current ~ 6 MA
- In-Bore Time ~ 8 – 10 msec

Figure 26. Exploring the Possibilities of a Naval Electromagnetic Railgun (Adapted from the NDIA 38th Annual Gun, Ammunition, and Missiles Symposium, 2003)

However, in order to defeat the BM in the worst case scenario, the requirement and the capabilities for the railgun in BMD is as shown in Table 4[65]. The projectile would be miniaturized in order to achieve the higher speed, but would still be guided and steered toward the target in flight.

Launch Velocity	10 km/s
Range	4,400 km
Flight Mass	2 kg
Guidance	Global Positioning System (GPS)/Inertial Navigation System (INS)
Firing Rate	16 ~ 20 rounds per minute

Table 4. Railgun Requirements to Meet Worst Case Scenario for BMD

Interaction of a high-speed interceptor with the targeted BM causes high-shock transmission throughout the structure, catastrophic failure, and other degradation effects. In addition, the higher energy impact causes adiabatic heating and ignition of flammable materials, thus creating an explosion and deflagration of stored ammunitions and fuel. The high temperature would destroy any chemical or biological agents in the missile.

5.4.3.3 Estimated Cost per Engagement

According to the *Technical Intelligence Bulletins*,[66] the future U.S. Navy railgun uses 5-7 gallons of fuel per launch. The cost per launch of a projectile using a railgun is estimated to be $5K-$10K. If a salvo of 6 shots were fired against the BMe,

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[65] *Faculty Advisor's Note:* There are four major technical challenge areas associated with the transition of the railgun to the fleet. These are Barrel/Rail Life, Pulsed Power Management, Ship Integration, and Projectile Material and Guidance. Barrel/Rail Life addresses the issues associated with developing a material lining system which can withstand the repeated multiple launches required by the BMD mission. Pulsed Power Management encompasses the shipboard system required to store and deliver the significant amounts of pulsed power required for firing of the railgun. Ship Integration issues include all of the ship design requirements associated with the railgun including EMI/EMP effects and heat rejection. Projectile Material and Guidance addresses the significant challenges associated with Atmospheric heating and projectile guidance. Creating a railgun with the parameters in Table 4 is not feasible given current technologies associated with the four major technical challenge areas, especially as they relate to system requirements for the firing rates, guidance, and top-end projectile velocities used in this study.

[66] Headquarters, Department of the Army, *Technical Intelligence Bulletins*, Vol. 7, No. 5, September-October 2002.

the cost would be $30K-$60K, which is still considerably lower than using a conventional missile.

However, this cost only accounts for the launch of an inert projectile. If guidance of the projectile is required, the cost of the projectile would increase. In addition, development of the railgun would be considerable given that it is an immature technology.

5.4.3.4 Feasibility of Guidance and Maneuverability in a Railgun-Launched Projectile

A projectile launched using a railgun experiences very high Gs, with current projections for a planned U.S. Navy application having values exceeding 45,000Gs, as listed in Figure 26. Even though GPS/INS guidance units have been successfully tested to 28,000Gs, which is the G-force experienced in a conventional launch method, considerable development is necessary to attain accelerations needed for future implementation.

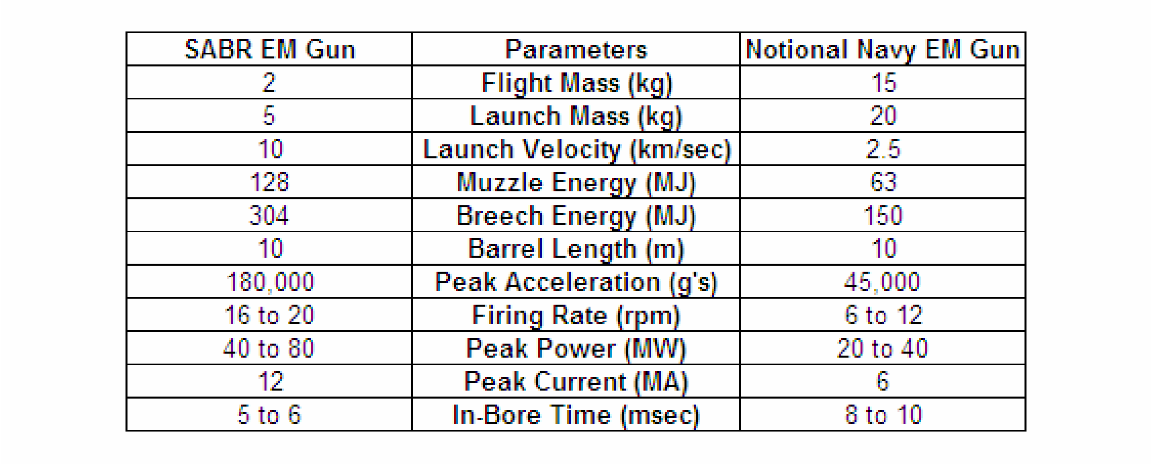
Control surfaces or fins would provide the projectile limited maneuverability in the low atmosphere—and have no effect in the upper atmosphere or when exo-atmospheric. The increase in speed would cause the turning radius of the projectile, or the maneuverability to decrease correspondingly. Given the limitation of the maximum G-force the projectile can operate, a two-fold increase in the velocity would increase the turning radius of a steerable projectile by four.

Due to the small mass of the projectile, future development on the complementing miniaturization of the GPS/INS units is needed. In addition, the effectiveness and maneuverability of the control surfaces on a high-speed projectile needs to be further examined.

5.4.3.5 Technological Challenges

Due to the large current, friction, and high temperature produced during a launch, the rails undergo tremendous erosion. Thus, the rails need to be structurally strong, conductive, and possess the properties to withstand erosion at very high temperature. Current materials used in the railgun development are not durable and are often limited to a one shot per service interval.

The power supply must be able to deliver large currents. Pulsed alternator technology could be used in the railgun, however, the technological challenge would be the synchronization of the multiple alternators during discharge. This would require careful attention to the design of the pulsed power supply control system. However, in order to defeat the BM in the worst case scenario, the approximate required capabilities for the railgun in BMD are listed in Table 4-1[67] and are compared to the Notional Navy EM Gun.



SABR EM Gun	Parameters	Notional Navy EM Gun
2	Flight Mass (kg)	15
5	Launch Mass (kg)	20
10	Launch Velocity (km/sec)	2.5
128	Muzzle Energy (MJ)	63
304	Breech Energy (MJ)	150
10	Barrel Length (m)	10
180,000	Peak Acceleration (g's)	45,000
16 to 20	Firing Rate (rpm)	6 to 12
40 to 80	Peak Power (MW)	20 to 40
12	Peak Current (MA)	6
5 to 6	In-Bore Time (msec)	8 to 10

Table 4-1. Contrast of the SABR Railgun and the Notional Navy Railgun

5.5 PHYSICAL MODELING

Modeling of the BM threat and the interceptors is based on physical properties evolved through many different levels of detail, with the initial layer being pure ballistic trajectory based on Newtonian physics. The System Model uses these initial calculations to provide a starting point for the Time of Flight (TOF) aspect of the interceptor's engagement of the BM threat. Of the physical models developed for this study, the BM threat model was the most challenging because it required the greatest degree of fidelity when it came to the physical modeling. Once the BM threat model was completed, it was then modified to be used as an interceptor model.

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[67] *Faculty Advisor's Note:* Although the project parametric results examine alternate capabilities needed to meet the future threat, the report does not address the technological aspects of creating a physically feasible railgun to achieve the top-end performance that would be needed to meet the worst case scenarios used in the study.

The modeling of the trajectory for the threat missile and the railgun utilize physics-based modeling in spreadsheets to produce the desired results. The models are purely deterministic and did not require anything more complicated than Microsoft Excel 2003. Microsoft Excel 2003 was also used to convert Latitude and Longitude Coordinates into XY-Cartesian Plane Coordinates since this can be accomplished through relatively simple trigonometric calculations. The results of these high-resolution models were then transferred to the system model. Extend version 6.0.6 was used to house the system model and simulate the various scenarios because of its capability with discrete events cueing.

5.5.1 Initial Interceptor Time of Flight Inputs to System Model

The key component for interceptor flight times was a time of flight correction based on a linear distance to the target and accounts for flight time along a ballistic trajectory. For the Directed Energy and Particle Beam Alternatives, due to the near speed of light engagement of the intercept, the only correction needed was the time required to deposit enough energy to neutralize the target. This correction was 2 seconds and 1×10^{-6} seconds, respectively. The Missile Alternative assumed thrust vector control and missile frame control surfaces to maintain a linear flight path toward intercept of the BM threat and no time correction was utilized. Since the two previous assumptions cannot be made for a railgun round with no propulsion and traveling significantly slower than the speed of light, separate calculations were made to compensate for the actual ballistic flight time given a linear range and time solution to the target.

Direct integration of an interceptor trajectory model as a fire control solution to a BM threat trajectory was not implemented during the course of modeling and simulation in this study. Rather, a TOF correction factor was used to allow the system model to calculate the engagement parameters with a time of flight that was an accurate approximation of the actual TOF experienced by the railgun projectile.

A railgun interceptor with an expected maximum effective range of 4,400 km was used in the system model. To properly account for the TOF a simple trajectory was calculated based solely on Newtonian physics.

Ignoring all factors except velocity (v) and gravitational acceleration at the surface of the earth (g_o), the total flight time of the projectile, time to apex, down range and altitude positions were calculated. The results were then used to calculate the needed time adjustment for a ballistic trajectory given a linear range.

$$V_{ox} = V_o * \cos\theta$$

$$V_{oy} = V_o * \sin\theta$$

$$X = V_{ox} * t$$

$$Y_{\max} = V_{oy} * t - \frac{1}{2} * g * t^2$$

$$t = \frac{V_{oy}}{g} \pm \sqrt{\frac{V_{oy}{}^2}{g^2} - \frac{2 * Y_o}{g}}$$

If Y_o=0, then $t = \frac{2 * V_{oy}}{g}$.

Since the maximum effective range is of interest, it can be assumed that this range is closely approximated by the range in the horizontal plane corresponding to the $Y_{\max}$ coordinate, and therefore, the TOF of interest is half the total TOF.

$$t = \frac{V_{oy}}{g}$$

This equation can now be used to find the X coordinate when apex is attained.

$$X_{@apex} = V_{ox} * \frac{V_{oy}}{g}$$

When V_o=10 km/sec, ~30°, the resulting (X,Y) position is (4.44, 1.30), in meters. This point is then converted into a range, in kilometers, from the origin (0, 0) and divided by V_o to yield the linear TOF, 0.463 sec. The ballistic TOF under the same conditions to apex is 0.515 seconds. The resulting TOF Correction Factor is 0.116 seconds per kilometer. Therefore, in the system model the linear range to the target was multiplied by 1.12 to approximate the flight time required by the projectile to intercept the target.

A two-sample, two-tailed z-Test for means of the actual ballistic trajectory flight time correction for a linear range compared to the simple linear range and time approximation has a resulting p-value of 3.1042×10^{-12}. Based on this analysis, there is no a significant difference in the calculated flight time correction and the initial correction used in the Extend system model at a confidence level near unity. As a result, the original TOF correction was not changed in the system model to retain as much continuity as possible.

5.5.2 Ballistic Missile (BM) Threat Model

The modeling of the BM threat went through several stages. After an analysis of the problem, it was decided to implement a deterministic model that modeled the trajectory from a given launch location to a predetermined target. It was not deemed necessary to include varying weather conditions or attempt to model the possibility of mechanical failure in the threat missiles; conditions that could cause a failed launch or deviation in trajectory. This was done both to reduce the complexity of the models in areas that were not as important to the final results and to give the adversary the benefit of a perfectly functioning missile system and optimal weather conditions. After all, the project was to develop an interception system, not build a better threat missile. This is admittedly unrealistic, but it does provide a worst-case scenario for the interceptors to deal with, which, in this case, was thought to be more important than absolute realism.

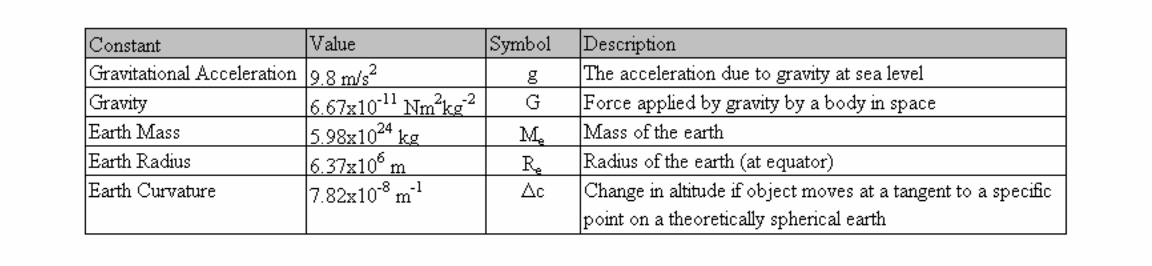
Initially, the model was created by simply using the trajectory implied by basic Newtonian physics without taking the effects of air resistance, varying gravitational pull, or the curvature of the earth into account. Needless to say, the results were not particularly close to those that were anticipated after consulting various published works or the Strategic and Theater Attack Modeling Process (STAMP) software, obtained in order to check the results.

As this is a simple deterministic model, a spreadsheet was used to perform the described calculations. The remainder of this chapter describes first the user-defined parameters, then the physical constants used, and finally, the actual equations used in the model.

The model used the parameters listed in Tables 5 and 6 to describe the threat model.

Parameter	Units	Symbol	Description
Total Mass	kg	M_t	The total mass of the missile
Warhead Mass	kg	M_w	The mass of only the warhead component
Propellant Mass	kg	M_p	The mass of only the propellent
Dry Booster Mass	kg	M_b	The remaining mass of the missile
Number of Stages	#	stg	The number of stages
Burn Time	sec	t_b	The total time taken for the boost phase
BM Frame Height	m	H_f	The height of the missile frame (no warhead)
BM Frame Diameter	m	D_f	The diameter of the missile frame
Warhead Height	m	H_w	The height of the warhead (cone)
Warhead Diameter	m	D_w	The diameter of the base of the warhead
Theta	deg	θ	Initial angle of launch
Divert Angle	deg	f	Tip over angle
Divert Time	sec	t_d	Time before tip over
Specific Impulse	sec	Isp	Thrust per unit of propellant
m-dot	kg/sec	$\dot{m}$	Mass flow rate of the missile propellant during boost phase
Number of Engines	#	eng	The number of engines on each stage of the missile
Time Step	sec	Δ_t	The time step used in the calculations
Thrust Control	#	ΔThrust	Reduces thrust to simulate throttle control
Tip-over Rate	radians	$\Delta\varphi$	Change in Angle of Attack from control surfaces

Table 5. List of Threat Model Parameters



Constant	Value	Symbol	Description
Gravitational Acceleration	$9.8\ m/s^2$	g	The acceleration due to gravity at sea level
Gravity	$6.67x10^{-11}\ Nm^2kg^{-2}$	G	Force applied by gravity by a body in space
Earth Mass	$5.98x10^{24}\ kg$	M_e	Mass of the earth
Earth Radius	$6.37x10^6\ m$	R_e	Radius of the earth (at equator)
Earth Curvature	$7.82x10^{-8}\ m^{-1}$	Δc	Change in altitude if object moves at a tangent to a specific point on a theoretically spherical earth

Table 6. List of Constants Used by Threat Model

The following equations show how the threat missile's trajectory was modeled to produce x and y coordinates for any given time assuming the missile parameters listed in Tables 5 and 6 have been entered. The equations are given in this order, as many of them are dependent on the results of earlier equations in the sequence and would not make sense otherwise.

Angle of Attack (AOA)

The AOA is set to the initial theta value (which was usually set to 90 degrees) until the divert time, which simulated the initial tip over of the missile after it has left the launcher. Rather than attempt to model all of the forces acting on the missile that force it to slowly tip over as the missile passes the apex of its flight and begins its decent, the model takes a tip-over rate that, after the burn is finished, causes the AOA to continue to increase all the way up until impact. This tip-over rate begins with a positive sign, becomes zero at the apex and then becomes more and more negative it descends. This approximation avoids a possible source of error where the lift force would remain positive even after the apex, when it should be negative as the airflow begins to push the warhead downwards.

$$\theta = \phi + \Delta\phi$$

Lift Coefficient (C_L) and Drag Coefficient (C_D)

At hypersonic velocities, the lift and drag coefficients are found using the equations defined by hypersonic theory.[68] Due to the rapid progression through the various stages of subsonic and supersonic velocities (<30 sec) the choice was made to only model the hypersonic effects and ignore the minor errors produced by not fully modeling this area. The results of the simulations, when compared to validated models, bears out this assumption. As shown in Figure 27, the first two equations show the calculation for lift and drag coefficient at hypersonic speeds. The second two equations show the calculation of the angle of attack given the shape of the projectile.

$$C_L = 2\sin^2(\alpha)\cos(\alpha)$$

$$C_D = 2\sin^3(\alpha)$$

$$\alpha_{nose} = \frac{\gamma}{2} + \theta$$

$$\alpha_{frame} = \theta$$

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[68] Jeff Scott, "Hypersonic Theory," online tutorial, http://www.aerospaceweb.org/design/waverider/theory.shtml, 2000, accessed 20 April 2006.

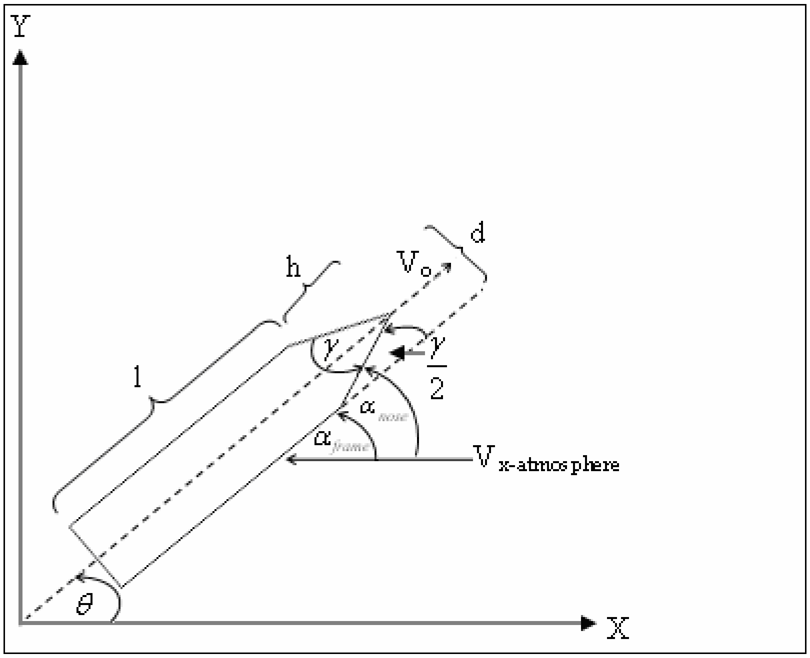

Figure 27. Graphical Representation of Angle of Attack Calculation

Given the dimensions of the BM, α can be directly calculated.

$$\alpha_{nose} = \tan^{-1}\left(\frac{d}{2*h}\right)+\theta$$

Gravitational Effect (g_c)

Due to the high altitudes obtained by the BMs, it was deemed necessary to account for the reduction in the effects of gravity felt by the objects as they travel up out of the atmosphere. This was found using the equation:

$$g_c = \frac{G*M_e}{(R_e+h)^2}.$$

In this equation, G, M_e, and R_e are constants and h is the current altitude of the missile.

Acceleration Force (F_a)

The acceleration provided by the thrust of the engines is found by multiplying the effective force of gravity to the product of the flow rate, specific impulse, and number of engines divided by the total mass of the missile.

$$Thrust = \dot{m} * I_{sp} * eng$$

$$F_a = \left(\frac{\dot{m} * I_{sp} * eng}{M_t} \right) * g_e$$

Since the threat missile selected for this project uses a solid fuel, the fuel flow rate can not be adjusted as in liquid fuel systems. To achieve the same effect, vents are used in solid fuel rockets to reduce the chamber pressure and the resulting thrust exiting the nozzle.[69] To account for this in the model, a mathematical throttle control was introduced so that the appropriate ranges could be obtained and a new F_a equation formed.

$$F_a = \left[\left(\frac{\dot{m} * I_{sp} * eng}{M_t} \right) * g_e \right] * \Delta Thrust$$

The total force on the rocket can be determined by

$$F_a^{'} = \sqrt{(F_a * \cos(aoa))^2 + (F_a * \sin(aoa) - g_e)^2} \; .$$

Temperature (T)

To find the atmospheric temperature at various altitudes, the standard atmosphere model provided on the National Aeronautics and Space Administration (NASA) Website was used. The atmosphere for the purposes of this model is divided into three layers and the temperatures are found in the following equations.

$$(h \geq 25,000m)T = -131.21 + 0.00299h$$
$$(11,000m \leq h < 25,000m)T = -56.46$$
$$(h < 11,000m)T = 15.04 - 0.00649h$$

Rho (ρ)

Rho is defined as the density of the fluid an object is passing through. In air it is related to atmospheric pressure in the following way.

$$\rho = \frac{P}{0.2869 * (T + 273.1)}$$

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[69] Frederick S. Simmons, *Rocket Exhaust Phenomenology*, Aerospace Press Series, AIAA, 2000, Chapter 1.

To find the atmospheric pressure, the NASA Website was again utilized to obtain the following equations based on the altitude and the temperature.

$$(h \geq 25{,}000m)P = 2.2488 * \left[\frac{T + 273.1}{216.6}\right]^{-11.388}$$

$$(11{,}000m \leq h < 25{,}000m)P = 22.65e^{(1.73-0.000157h)}$$

$$(h < 11{,}000m)P = 101.29 * \left[\frac{T + 273.1}{288.08}\right]^{5.526}$$

Lift Force (F_L) and Drag Force (F_D)

The lift and drag forces are found using the formulae given below. Due to the limitations of the model, the previous time steps velocity and rho were used when calculating the forces for the current forces to avoid a circular reference in the code, but using a time step of one second caused the differences to be insignificant.

$$F_L = \frac{1}{2} * \rho * V^2 * C_L * A$$

$$F_D = \frac{1}{2} * \rho * V^2 * C_D * A$$

Here the variable A is the cross-sectional area of the warhead found using the following formula for the surface area of a cone (without the base):

$$A = (\pi * r)\left(r + \sqrt{r^2 + h^2}\right)$$

Missile Mass (M_c)

The mass of the missile is not constant. During the boost phase, the propellant is being used at a given amount as captured in the parameter mdot ($\dot{m}$). Once the boost phase is complete, then the mass becomes constant for the rest of flight. The model assumes that the threat missile is a single-stage missile with no boosters being used.

$$M_C = M_t - (\dot{m} * t)$$

$$M_C = M_t - M_p$$

Total Force Acting on Missile (F_t)

The total force acting on the missile at any time is the magnitude of its two component forces.

$$F_t = \sqrt{F_x^2 + F_y^2}$$

These component forces are found by adding the forces resulting from the thrust provided by the missile engine(s), the lifting and dragging forces, and in the case of the y component, the effective force of gravity.

$$F_x = M_c * F_a * \cos(aoa) - F_L * \cos\left(\frac{\pi}{2} - aoa\right) - F_D * \cos(aoa)$$
$$F_y = M_c * F_a * \sin(aoa) - M_c * g_e + F_L * \sin\left(\frac{\pi}{2} - aoa\right) - F_D * \sin(aoa)$$

Once the boost phase is complete, the acceleration forces become zero and the remaining forces acting on the missiles are shown below.

$$F_x = -F_L * \cos\left(\frac{\pi}{2} - aoa\right) - F_D * \cos(aoa)$$
$$F_y = -M_c * g_e + F_L * \sin\left(\frac{\pi}{2} - aoa\right) - F_D * \sin(aoa)$$

Velocity (V)

The current velocity is found by adding the product of the current forces acting on the missile and the time step divided by the current mass of the missile. The component velocities are then the velocity multiplied by the cosine or sine of the missile's angle of attack for the x and y components, respectively. The AOA is used in order to approximate the direction of travel for the missile at any given time.

$$V = V_{(t-1)} + \frac{F_t * \Delta t}{M_c}$$

$$V_{xa} = V * \cos(aoa)$$
$$V_{ya} = V * \sin(aoa)$$

Location

The current location of the missile is then calculated in the x-y plane by modifying the previous (or initial) position by adding the component velocity multiplied by the time step. For the y direction, the curvature of the earth is taken into account by adding a constant value for every meter traveled in the x direction, Table 6.

$$
\begin{aligned}
&x = x_{(t-1)} + V_{xa} * \Delta t \\
&y = y_{(t-1)} + V_{ya} * \Delta t + \Delta c * \Delta x \\
&\left(\Delta x = x - x_{(t-1)}\right)
\end{aligned}
$$

This information is then taken and provided to the other models to determine the necessary placement of interceptor platforms and interceptor capabilities requirements.

The following possible sources of error have been identified:

- The AOA calculation is an approximation, as the actual physical characteristics of the missile and warhead beyond the height and diameter are not readily available especially for an unclassified document.
- The lift and drag forces are only modeled using hypersonic velocities since it takes a very short period of time to move through subsonic, transonic, and supersonic velocities and the differences were considered insignificant.

After taking these factors into account, the results were, on average, within 0.05% of the expected impact range given by STAMP for the 1,000 km-3,000 km range (Figure 28). The apex and ratio between apex and impact range were also compared to ensure that the missile path was correct. The apex calculations were within 0.13% of the expected values and the ratios were within 0.15%. This shows that the model is at least functionally correct for the ranges of interest. STAMP was used to validate the model because it was originally used by the MDA to model BM threats. The program remains technically correct and was available for use in validating the threat model. The fundamental software does not require the extra system integration features provided by its successor to be used.

Given that the overall system is a conceptual model and not being proposed for production, the basic threat model as developed here is sufficient to be used as inputs for the platform and interceptor models that are the actual focus of the project.

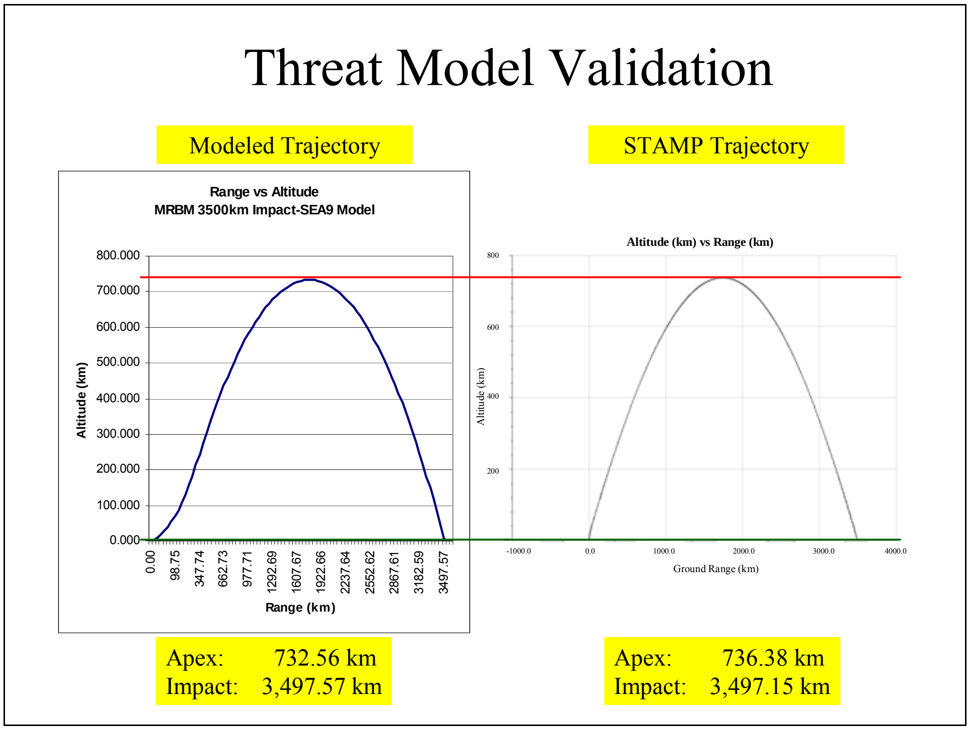

Figure 28. Comparison of Threat Model and STAMP Trajectories

5.5.3 Latitude and Longitude Inputs to Physical Model

Once the refined BM threat model was completed, a method to place the points of interest into a usable grid was needed to enable modeling a scenario in any given region of the world. Since latitude and longitude coordinates are a universally known coordinate system, they were used to designate launch sites, target sites, and ship positions (or other defensive sites).

If the earth could be considered flat, the difficulty in creating a planar coordinate system would be negligible. A tool was developed to transform a spherical coordinate system, such as latitude and longitude, into an XY-Cartesian plane coordinate system. Latitude and longitude positions given in the degree, minute, second format need to be converted into a decimal form to be used by the model.[70]

$$DecimalDegree = Degree + \frac{Minute}{60} + \frac{Second}{3600}$$

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[70] Anthony P. Kirvan, 1997, Latitude/Longitude, *NCGIA Core Curriculum in GIScience*, http://www.ncgia.ucsb.edu/giscc/units/u014/u014.html, posted 14 April 2006.

The following formula is used to provide great circle ranges in kilometers from a given reference point to an arbitrary point in the system. This aligns the calculated grid to identify relationships between each point and the selected reference point.

$$D = \cos^{-1}\left[(\sin(lat_1)*\sin(lat_2)) + (\cos(lat_1)*\cos(lat_2)*\cos(|long_1 - long_2|))\right]*111.325$$

Although parallels of latitude decrease in length with increasing latitude, the variation is only 1.13 kilometers from the equator to the poles; the standard figure of 111.325 kilometers per degree of latitude can, therefore, be used.

The length in kilometers for a degree of longitude is not quite as simple. It is, however, a function of latitude. The relationship can be defined as $Longitude_{km/\deg ree} = 111.325[\cos(latitude_{\deg ree})]$.[71]

This relationship, however, is only valid when the path of travel remains on the same line of latitude. This restriction is not acceptable for modeling paths of travel that transcend lines of latitude and lines of longitude. In order to account for the changing length of a degree of longitude as the path of travel also crosses lines of latitude, the relationship between one degree of latitude and length of longitude was explored and identified (Figure 29). The equation $y = 0.0002x^2 - 0.0408x + 0.0676$, yields an R^2 of 0.9993 and therefore used in the calculation of the longitude portion of the XY-Cartesian coordinate based on the degree of latitude. The resulting equations used to plot latitude and longitude positions in a Cartesian plane.

$$\Delta Latitude = \Delta Lat = {}^\circ Lat_{po\text{int}} - {}^\circ Lat_{reference}$$

$$\Delta Longitude = \Delta Long = {}^\circ Long_{po\text{int}} - {}^\circ Long_{reference}$$

$$Latitude(km) = {}^\circ\Delta Lat * 111.325$$

$$Longitude(km) = {}^\circ\Delta Long * \left[111.325*\cos({}^\circ Lat_{decimal}) - 0.0002*{}^\circ\Delta Lat^2 - 0.0408*{}^\circ\Delta Lat + 0.0676\right]$$

---

[71] Anthony P. Kirvan, 1997, Latitude/Longitude, NCGIA Core Curriculum in GIScience, http://www.ncgia.ucsb.edu/giscc/units/u014/u014.html, posted 14 April 2006.

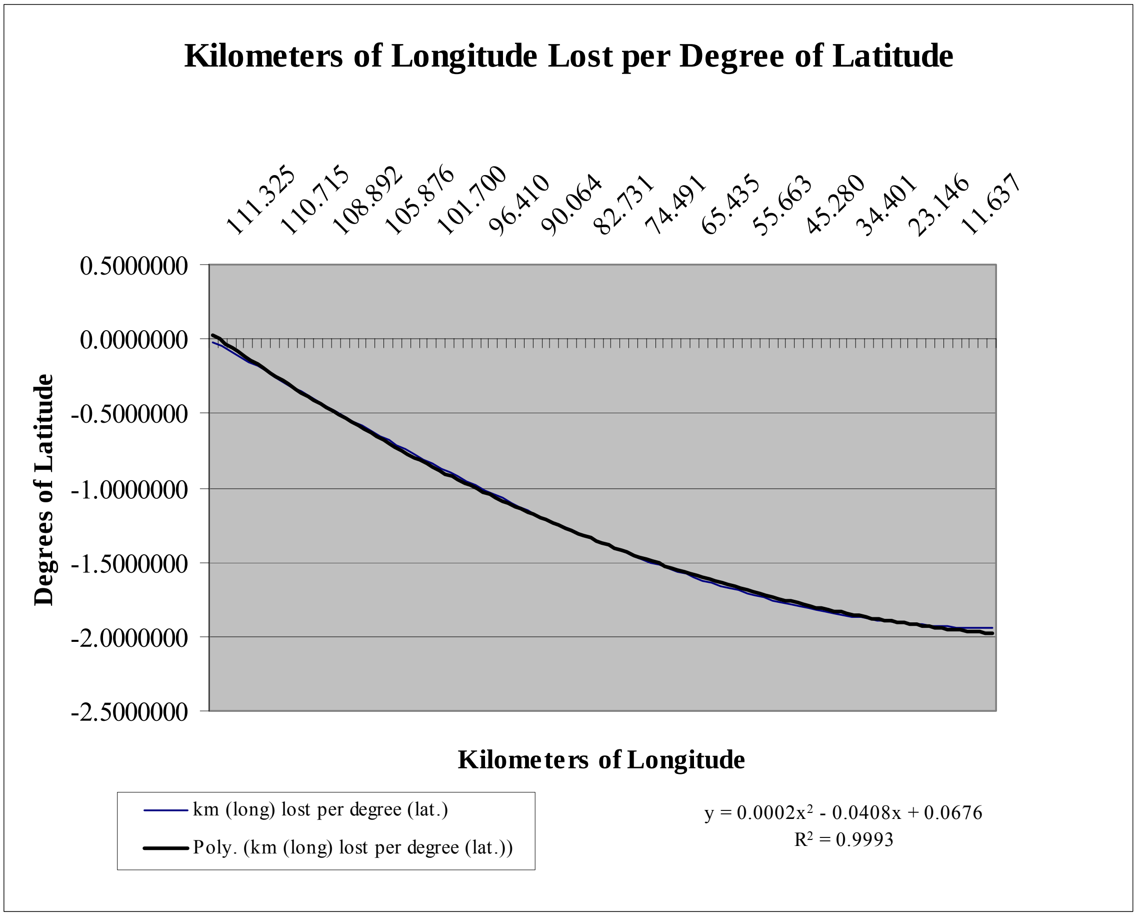
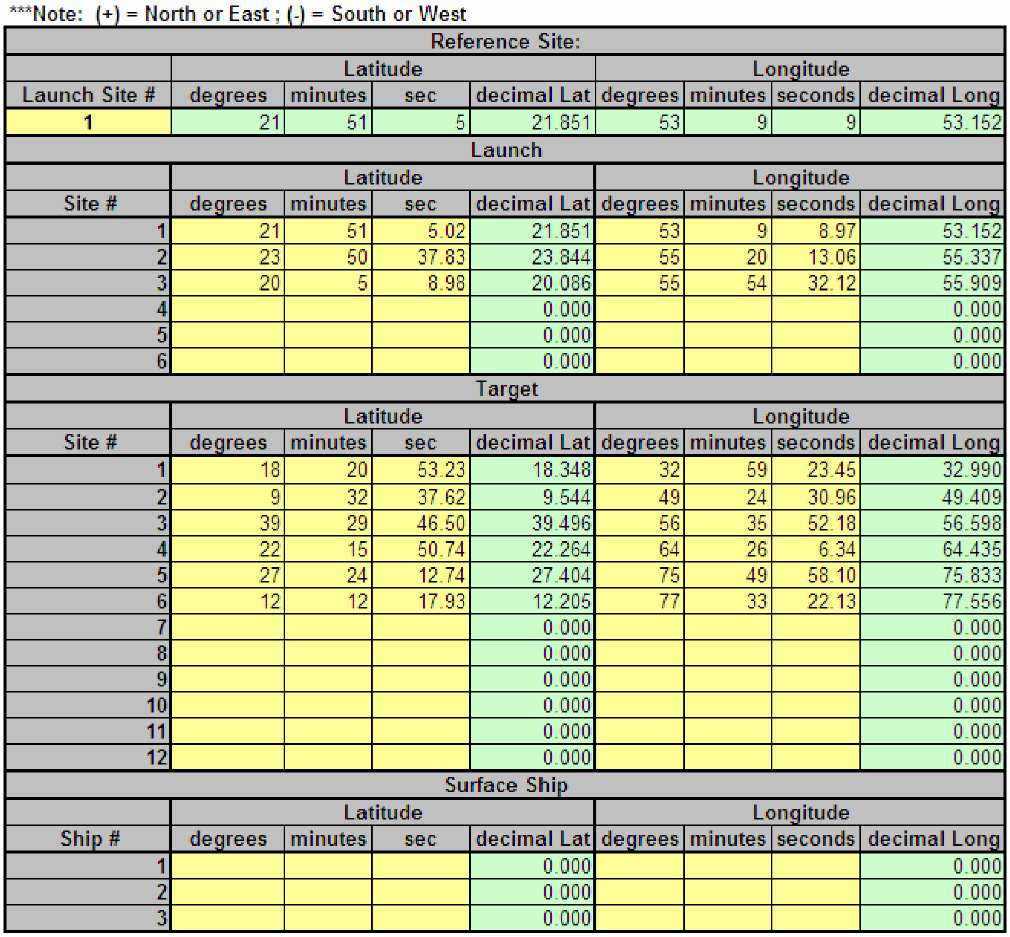


Figure 29. Kilometers of Longitude Lost per Degree of Latitude Crossed

This graph describes the relationship between the latitude and the kilometers that make up any particular degree of longitude.

Table 7 shows the Geographic Input Table used to enter the latitude and longitude coordinates of up to 6 launch sites, 12 target sites, and 3 ship sites. The reference site is selected by a drop-down menu tied to the launch site table. The use of the reference site enables the model to set the origin of the XY-Cartesian Plane. Due to the inherent error incurred by converting an ellipsoid coordinate system to a planar coordinate system, the reference site that yielded minimal error in conversion was used.

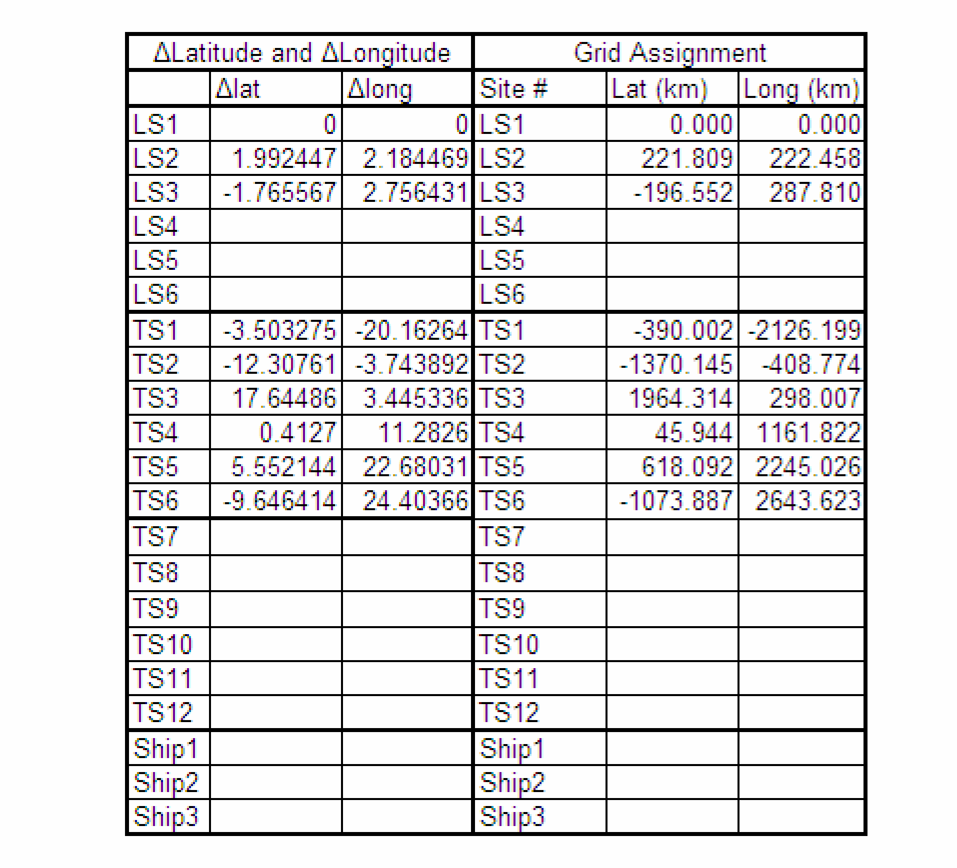


***Note: (+) = North or East ; (-) = South or West

Reference Site:								
	Latitude				Longitude			
Launch Site #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1	21	51	5	21.851	53	9	9	53.152
Launch								
	Latitude				Longitude			
Site #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1	21	51	5.02	21.851	53	9	8.97	53.152
2	23	50	37.83	23.844	55	20	13.06	55.337
3	20	5	8.98	20.086	55	54	32.12	55.909
4				0.000				0.000
5				0.000				0.000
6				0.000				0.000
Target								
	Latitude				Longitude			
Site #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1	18	20	53.23	18.348	32	59	23.45	32.990
2	9	32	37.62	9.544	49	24	30.96	49.409
3	39	29	46.50	39.496	56	35	52.18	56.598
4	22	15	50.74	22.264	64	26	6.34	64.435
5	27	24	12.74	27.404	75	49	58.10	75.833
6	12	12	17.93	12.205	77	33	22.13	77.556
7				0.000				0.000
8				0.000				0.000
9				0.000				0.000
10				0.000				0.000
11				0.000				0.000
12				0.000				0.000
Surface Ship								
	Latitude				Longitude			
Ship #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1				0.000				0.000
2				0.000				0.000
3				0.000				0.000

Table 7. Physical Model Geographic Input Table

Table 8 shows the result of the conversion of latitude and longitude coordinates to an XY-Cartesian plane coordinate system. These calculated values were used in the model to plot the BM trajectory from launch through impact.



ΔLatitude and ΔLongitude			Grid Assignment		
	Δlat	Δlong	Site #	Lat (km)	Long (km)
LS1	0	0	LS1	0.000	0.000
LS2	1.992447	2.184469	LS2	221.809	222.458
LS3	-1.765567	2.756431	LS3	-196.552	287.810
LS4			LS4		
LS5			LS5		
LS6			LS6		
TS1	-3.503275	-20.16264	TS1	-390.002	-2126.199
TS2	-12.30761	-3.743892	TS2	-1370.145	-408.774
TS3	17.64486	3.445336	TS3	1964.314	298.007
TS4	0.4127	11.2826	TS4	45.944	1161.822
TS5	5.552144	22.68031	TS5	618.092	2245.026
TS6	-9.646414	24.40366	TS6	-1073.887	2643.623
TS7			TS7		
TS8			TS8		
TS9			TS9		
TS10			TS10		
TS11			TS11		
TS12			TS12		
Ship1			Ship1		
Ship2			Ship2		
Ship3			Ship3		

Table 8. Latitude and Longitude to Cartesian Plane Conversion Table

Validation of the ranges resulting from the method used to assign XY-Cartesian coordinates of the entered positions were then compared to the great circle ranges calculated directly from the latitude and longitudes of the entered coordinates. Referring to Figures 30 and 31, no significant difference was found at a 95% confidence level and the calculated XY-Cartesian plane coordinates were used to assign all positions in the system model.

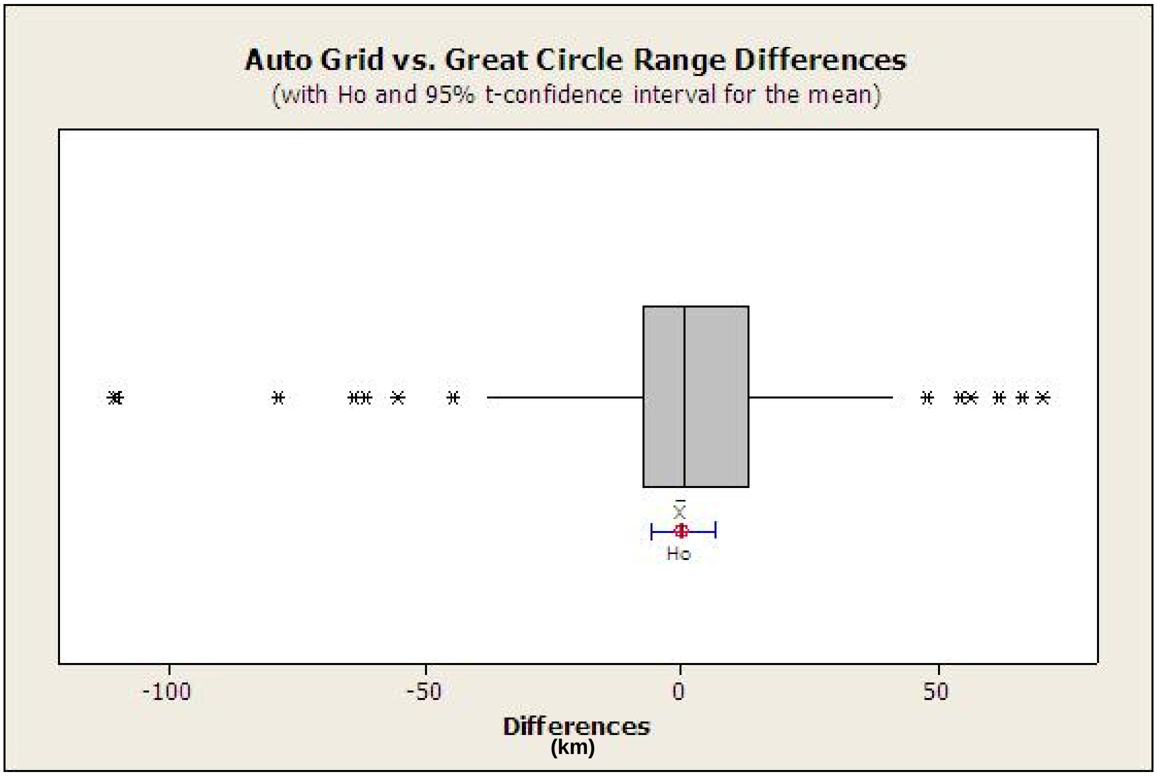
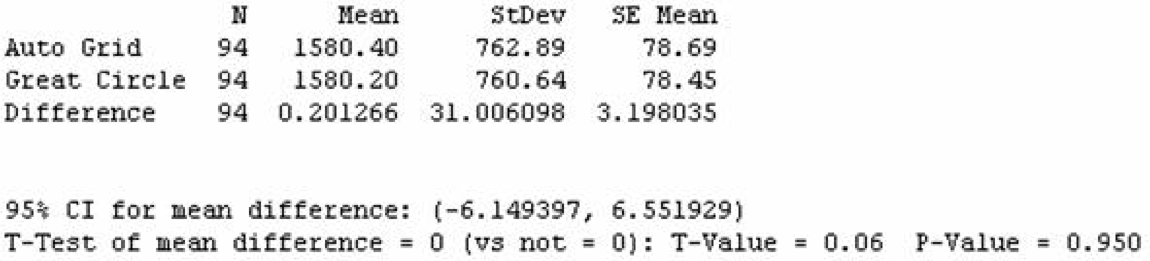


Figure 30. Auto Grid vs. Great Circle Range Differences



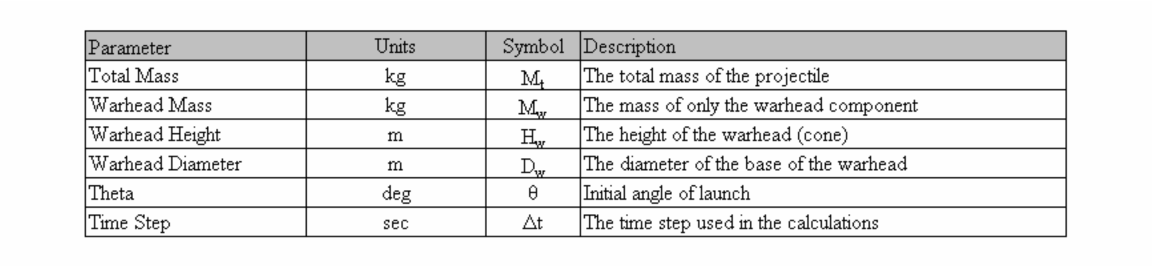
```
                N      Mean      StDev   SE Mean
Auto Grid      94   1580.40     762.89     78.69
Great Circle   94   1580.20     760.64     78.45
Difference     94  0.201266  31.006098  3.198035


95% CI for mean difference: (-6.149397, 6.551929)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.06  P-Value = 0.950
```

Figure 31. Statistical Results from Auto Grid vs. Great Circle Comparisons

5.5.4 Railgun Interceptor Model

The BM threat model was used as the primary input to the railgun interceptor model. To that end, many of the equations listed in Section 5.5.3 were used for the interceptor model. The primary difference between the models is the need for boost calculations and the integral velocities and forces acting on a BM during boost. The railgun interceptor does not have this requirement and the input of a muzzle velocity replaced the launch angle, tip-over, and boost aspects of the BM threat model. The model used the parameters listed in Table 9 to describe the railgun interceptor model.



Parameter	Units	Symbol	Description
Total Mass	kg	M_t	The total mass of the projectile
Warhead Mass	kg	M_w	The mass of only the warhead component
Warhead Height	m	H_w	The height of the warhead (cone)
Warhead Diameter	m	D_w	The diameter of the base of the warhead
Theta	deg	θ	Initial angle of launch
Time Step	sec	Δt	The time step used in the calculations

Table 9. List of Constants Used by the Interceptor Model

The following equations show how the round's trajectory was modeled to produce x and y coordinates for any given time assuming the railgun parameters in Table 9 have been entered. As in the BM threat model, the equations are given in this order as many of them are dependent on the results of earlier equations in the sequence and would not make sense otherwise. For the purposes of the railgun interceptor model, only the aspects that are different than those in the BM threat model will be discussed.

Angle of Attack (AOA)

The AOA is set to the initial theta value.

Lift Coefficient (C_L) and Drag Coefficient (C_D)

At hypersonic velocities the lift and drag coefficients are found using equations defined in hypersonic theory.[72] Due to the muzzle velocity of 10 km/sec, hypersonic effects were modeled in this area.

$$C_L = 2\sin^2(\alpha)\cos(\alpha)$$

$$C_D = 2\sin^3(\alpha)$$

For the railgun projectile, α is similar to the α_{nose} in Section 5.5.2.

$$\alpha = \frac{\gamma}{2} + \theta \text{ ; or } \alpha = \tan^{-1}\left(\frac{d}{2 * h}\right) + \theta$$

Total Force Acting on Missile (F_t)

The total force acting on the round at any time is the magnitude of its two component forces.

$$F_t = \sqrt{F_x^2 + F_y^2}$$

These component forces are found by adding the forces resulting from the launch, the lifting and dragging forces, and in the case of the y component, the effective force of

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[72] Jeff Scott, "Hypersonic Theory," http://www.aerospaceweb.org/design/waverider/theory.shtml, 2000, accessed 20 April 2006.

gravity. Since there is no acceleration after launch, the actual velocity of the projectile was used to compute an equivalent F_a in order to calculate the forces in the total forces component planes.

$$F_a = \frac{M * V_t}{t}$$

$$F_x = M_w * F_a * \cos(aoa) - F_L * \cos\left(\frac{\pi}{2} - aoa\right) - F_D * \cos(aoa)$$

$$F_y = M_w * F_a * \sin(aoa) - M_w * g_e + F_L * \sin\left(\frac{\pi}{2} - aoa\right) - F_D * \sin(aoa)$$

This information is then taken and provided to the other models to determine necessary placement of interceptor platforms and interceptor capabilities requirements.

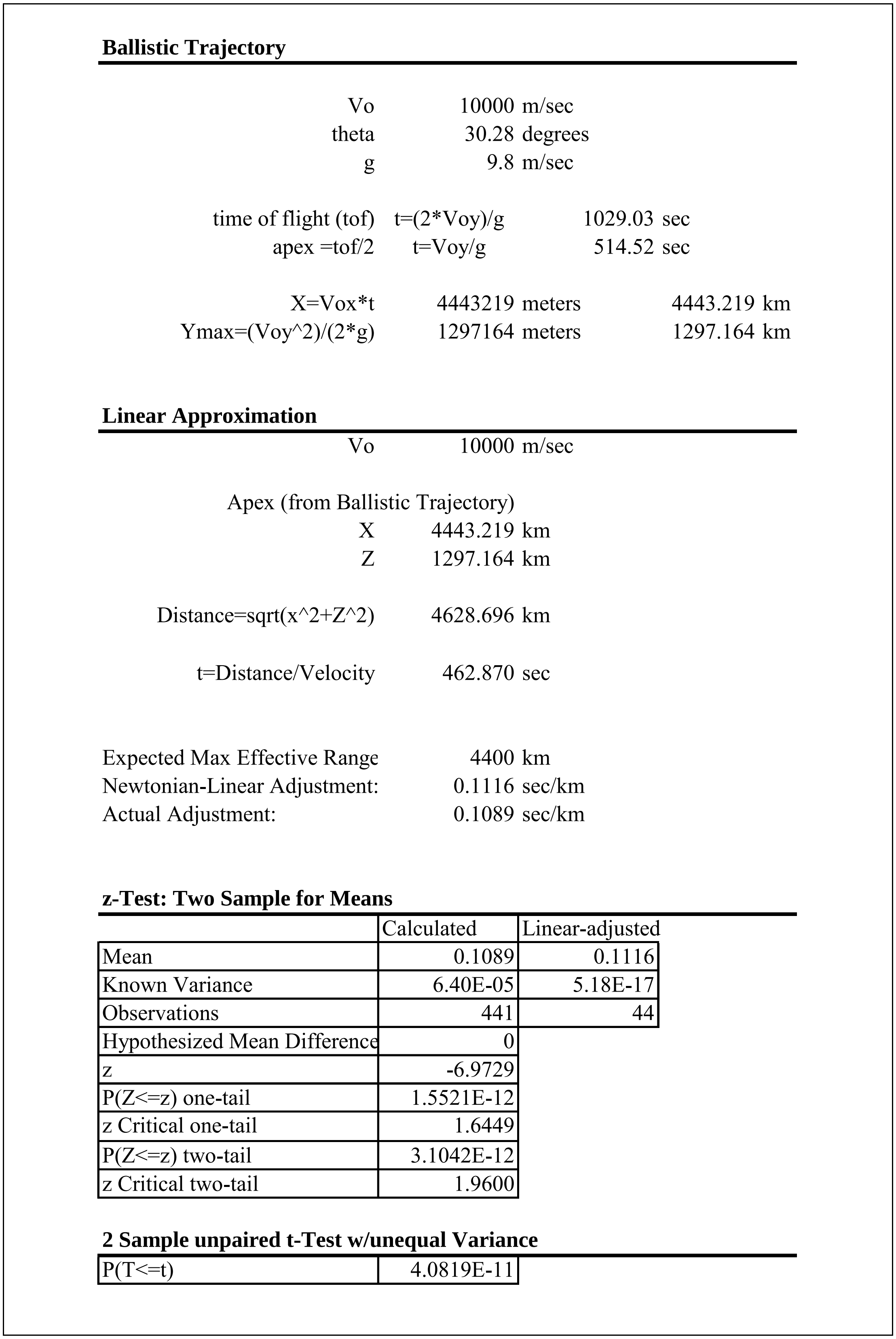
The following possible source of error has been identified:

- The AOA is set to the initial angle at the time of launch. The actual physical characteristics of the projectile beyond the height and diameter are not readily available since this is a conceptual design so further modeling is not possible without extensive guesswork. Incorporating effects of control surfaces or utilizing actual wind effects would yield more accurate results.

Given that the overall system is a conceptual model and not being proposed for production, the basic railgun interceptor model as developed here is sufficient to be used as inputs for the platform and interceptor models that are the actual focus of the project.

5.5.5 Interceptor Time of Flight (TOF) Inputs to the System Model

Once the refined trajectory models were completed, the TOF correction value was revisited to determine if its accuracy was sufficient for the modeling or if it needed to be changed. Figure 32 shows the comparison of the initial TOF calculation and correction factor versus the refined models results. The time correction factor shown for the refined model was obtained by using Microsoft Excel's Data Table functionality to vary the launch angle at 0.1° increments from 1.0° to 45.0° and recording the apex altitude, x-coordinate at apex, and the TOF to apex. The time per kilometer value was obtained for each line item by dividing the range by the flight time. The resulting value for each line item was then averaged, mean=0.1089, and statistically compared to the earlier correction factor of 0.1116. The results are also listed in Figure 32. With a resulting P-value < alpha (which is the default 0.05 in this case) the null hypothesis of equal means is rejected, resulting in support of the alternative hypothesis of unequal means, so the original value was kept to maintain continuity in the system model.



Ballistic Trajectory

Vo	10000 m/sec			
theta	30.28 degrees			
g	9.8 m/sec			
time of flight (tof)	t=(2*Voy)/g	1029.03 sec		
apex =tof/2	t=Voy/g	514.52 sec		
X=Vox*t	4443219 meters		4443.219 km	
Ymax=(Voy^2)/(2*g)	1297164 meters		1297.164 km	

Linear Approximation

Vo	10000 m/sec
Apex (from Ballistic Trajectory)	
X	4443.219 km
Z	1297.164 km
Distance=sqrt(x^2+Z^2)	4628.696 km
t=Distance/Velocity	462.870 sec

Expected Max Effective Range	4400 km
Newtonian-Linear Adjustment:	0.1116 sec/km
Actual Adjustment:	0.1089 sec/km

z-Test: Two Sample for Means

	Calculated	Linear-adjusted
Mean	0.1089	0.1116
Known Variance	6.40E-05	5.18E-17
Observations	441	44
Hypothesized Mean Difference	0	
z	-6.9729	
P(Z<=z) one-tail	1.5521E-12	
z Critical one-tail	1.6449	
P(Z<=z) two-tail	3.1042E-12	
z Critical two-tail	1.9600	

2 Sample unpaired t-Test w/unequal Variance

P(T<=t)	4.0819E-11

Figure 32. Statistical Comparison of Ballistic and Known Flight Times

5.6 PRELIMINARY DATA

5.6.1 Preliminary System Model

The preliminary system model is a discrete event model that was used for the purpose of choosing the best architecture or eliminating possible architectures. A discrete event model was used because the detect to engage sequence is quantified by a series of events**.** Although the model does not completely mimic reality, it provides a good approximation for the purposes of this project. Faults can be found with any model and there is always going to be a tradeoff between complexity and how much added insight it provides. There are six versions of this model that have small differences from model to model. The six different models represent the six different architectures that were investigated. The scenarios did not change the actual models, just the inputs. Figure 32-1 shows an overview of the preliminary system model. Decision variables are the various architectures the SABR team evaluated. There were no direct environmental factors in the model. However, system performance was varied to account for the environmental factors of three scenarios.

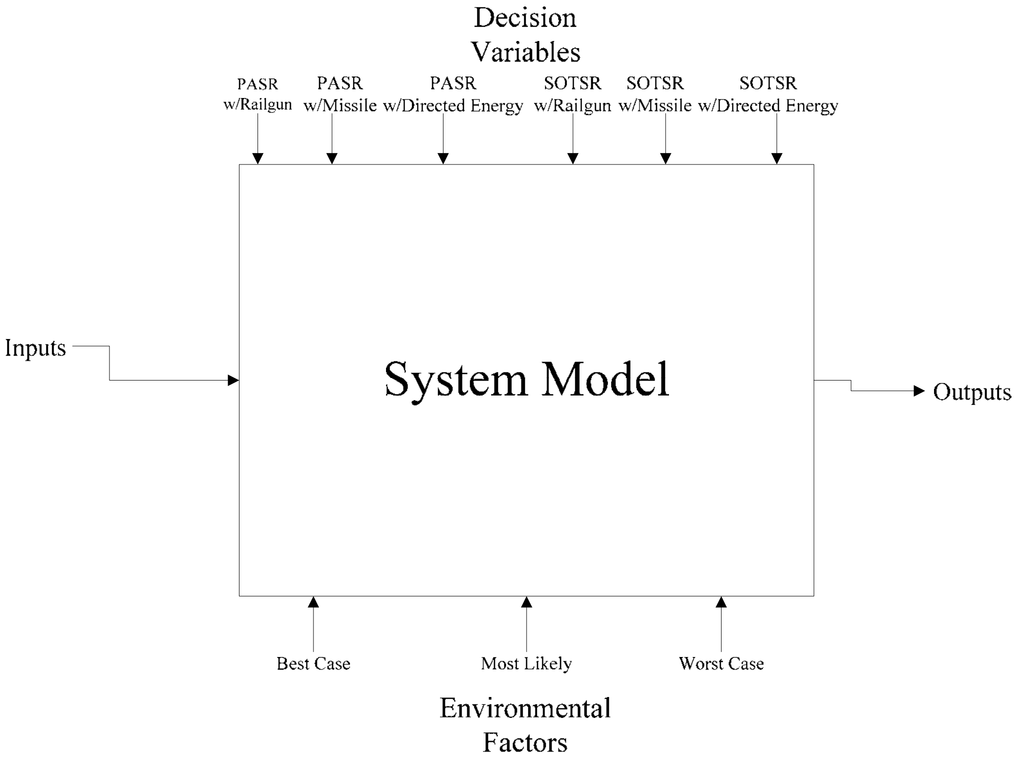


Figure 32-1. Preliminary System Model General Overview

5.6.1.1 Inputs

Figure 33 shows the block diagram of the overall integrated model. As can be seen from the diagram, the system model receives inputs from the BM threat model and utilizes these inputs during the detect to engage sequence. The system model also receives inputs through the notebook feature in Extend. These inputs represent various sensor and interceptor inputs. Inputs are broken into three major categories: threat model, commit stage, and interceptor. Commit stage is further broken down into organic and nonorganic inputs. The system model receives all of these inputs to simulate a ship's anti-ballistic missile response.

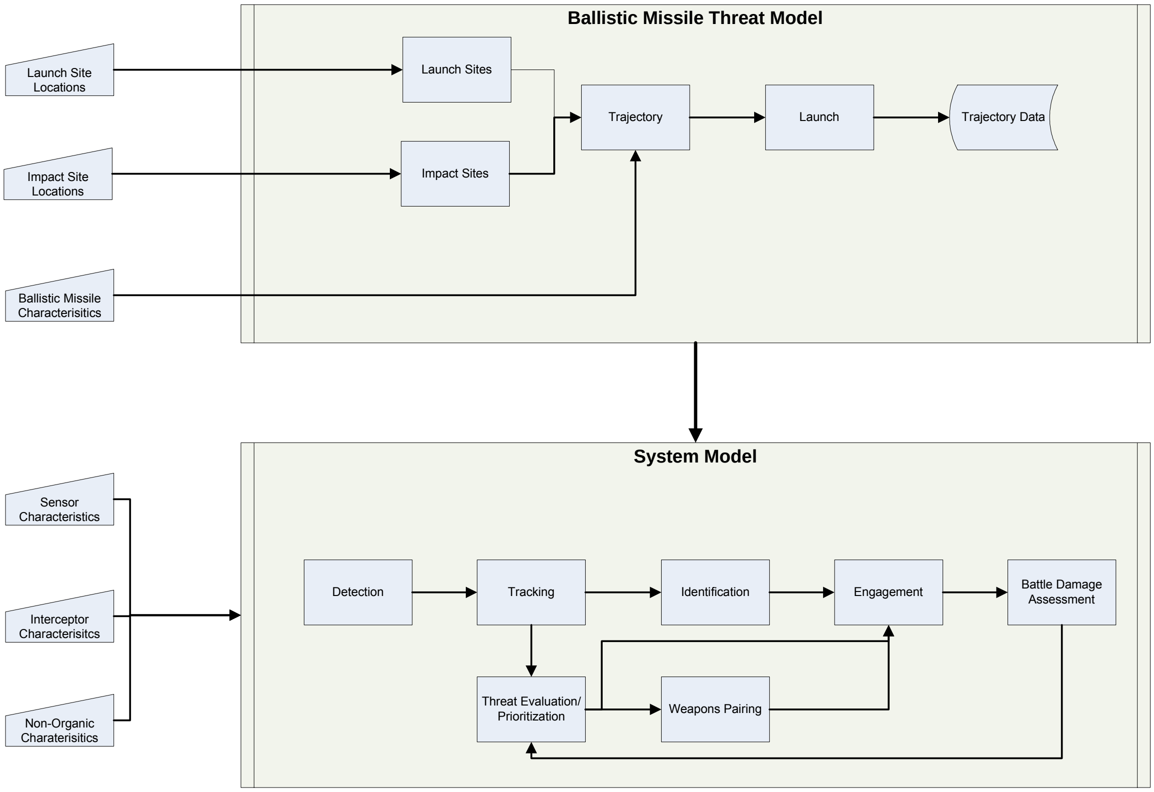


Figure 33. Integrated Models Block Diagram

5.6.1.1.1 Threat Model Inputs. The threat model used Microsoft Excel to calculate the trajectories of a BM from three launch sites to six targets. From the calculations, the missile's three-dimensional position is calculated for every second of missile flight. The missile's x, y, and z coordinates are in a table where Extend can obtain this information using "Data Receive" blocks. The x, y, and z positions of the missile are assigned to each object in Extend as attributes that are updated at various points throughout the model. Another major input from the threat model is the time to end of midcourse. This input is assigned as an attribute and used in "Decision Blocks" to determine when to hand off the missile to another asset.

5.6.1.1.2 Commit Stage Inputs. As per the design reference mission profile, inputs were divided into three different categories: best case, most likely, and worst case. The best case inputs are the optimum settings where all subsystems and components are functioning perfectly. Most likely has some delays assigned due to normal situations and events. Worst case settings are those when some systems or components are not functioning or are in a highly degraded state. The inputs were, for the most part, time delays. Rates were minimally used. Probabilities of detection and missed detection were also utilized.

Nonorganic Characteristics

Nonorganic inputs are the systems outside of the SABR platform. For the most part, they were attributed to satellite detection times, rates, and probabilities. Inputs that were not affected were the number of tracks that can be detected or held in the system. Delay times were accounted for due to system overload, weather, and communication delays. Table 10 shows the nonorganic inputs used for the various scenarios.

	Best Case		**Most Likely**		**Worst Case**	
Model Inputs	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
P(Sat Missed Detection)	0.01	Batch size=1	0.15	Batch size=1	0.3	Batch size=1
Sat Sweep Rate	6	1	8	1	10	2
Detection Delay for Satellite	0.5	0.4	3	0.5	10	2
Max Target Detected at a time (Sat only)	100	Constant	100	Constant	100	Constant
Processing Delay for Sat	0.001	0.0001	1	0.5	3	1
Max Processed at a time (Sat only)	1,000	Constant	1,000	Constant	1,000	Constant
Communications Delay for Sat	0.001	0.0001	1	0.02	2	0.1
Max detection simultaneously communicated by Sat only	1,000	Constant	1,000	Constant	1,000	Constant

Table 10. Nonorganic Asset Preliminary Model Inputs

Organic Characteristics

Organic inputs are those related to systems that are inside of the SABR platform. Two systems were evaluated. The multifunctional phased array was evaluated by itself. The next architecture that was evaluated was the phased array working in conjunction with the skin of the ship conformable radar. Attributes that were affected for each scenario were delay times for the system and probabilities. Many of the attributes remained constant for all three modeling scenarios. To keep the preliminary models simple, radar ranges were not how far the radar can detect. The ranges are how far the detection platform was from the launch site. It was kept this way to simplify future model refinement. Organic inputs used for all scenarios for the PASR are shown in Table 11. SOTSR inputs are shown in Table 12.

	Best Case		**Most Likely**		**Worst Case**	
Model Inputs	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Ship Detection Range (km)	500	Constant	625	Constant	750	Constant
Detection Height	13.86	Constant	21.92	Constant	31.81	Constant
P(Sensor System Detection)	0.95	Batch size=1	0.9	Batch size=1	0.85	Batch size=1
Sweep Rate for System	10	5	12	6	15	6
P(False Alarm)	0.02	Batch size=1	0.02	Batch size=1	0.02	Batch size=1
Detection Delay for Ship	2	1	4	1	8	2
Max targets simultaneously detected	1,000	Constant	1,000	Constant	1,000	Constant
Processing Delay for System	0.01	0.0001	1	0.2	2	0.5
Max targets processed at a time	1,000	Constant	1,000	Constant	1,000	Constant
Tracking Stage	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
P(keeping track)	0.95	Batch size=1	0.9	Batch size=1	0.9	Batch size=1
Time to reacquire track	5	2	6	2	7	2
Tracking Delay	1	0.1	2	0.5	3	0.7
Max Simultaneous Tracks	1,000	Constant	1000	Constant	1,000	Constant
Track Processing Delay	0.001	0.0001	1	0.5	2	0.5
Max Simultaneous Tracks Processed	1,000	Constant	1,000	Constant	1,000	Constant
Communicate Tracks Delay	0.001	0.0001	1	0.5	2	0.5
Max Tracks Communicated at Once	1,000	Constant	1,000	Constant	1,000	Constant
Identification Inputs	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Identification Delay	2	0.5	4	0.5	6	1
Max Targets Simultaneously Identified	1,000	Constant	1,000	Constant	1,000	Constant
Threat Evaluation Inputs	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Priority 1% to MC	80	Constant	80	Constant	80	Constant
Priority 2% to MC	60	Constant	60	Constant	60	Constant
Priority 3% to MC	40	Constant	40	Constant	40	Constant
Priority 4% to MC	20	Constant	20	Constant	20	Constant
Threat Evaluation Delay	5	1	6	1	7	1.5
Weapons Pairing Inputs	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Delay for Weapons Pairing	1.5	0.2	2.5	0.4	3.5	0.6
Max Targets Paired at a Time	1	Constant	1	Constant	1	Constant
BDA Stage	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Time to Conduct BDA	0.5	0.01	0.5	0.01	0.5	0.01
Max Simultaneous BDA	1,000	Constant	1,000	Constant	1,000	Constant
Prob. Good BDA	0.9	Batch size=1	0.9	Batch size=1	0.9	Batch size=1

Table 11. Phased Array Radar Preliminary Model Inputs

	Best Case		Most Likely		Worst Case	
Model Inputs	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Ship Detection Range (km)	1,000	Constant	1,500	Constant	2,000	Constant
Detection Height	92	Constant	120	Constant	150	Constant
P(Sensor System Detection)	0.95	Batch size=1	0.9	Batch size=1	0.85	Batch size=1
Sweep Rate for System	10	5	12	6	15	6
P(False Alarm)	0.02	Batch size=1	0.02	Batch size=1	0.02	Batch size=1
Detection Delay for Ship	2	1	4	1	8	2
Max targets simultaneously detected	1,000	Constant	1,000	Constant	1,000	Constant
Processing Delay for system	0.01	0.0001	1	0.2	2	0.5
Max targets processed at a time	1,000	Constant	1,000	Constant	1,000	Constant
Tracking Stage	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
P(keeping track)	0.95	Batch size=1	0.9	Batch size=1	0.9	Batch size=1
Time to reacquire track	5	2	6	2	7	2
Tracking Delay	1	0.1	2	0.5	3	0.7
Max Simultaneous Tracks	1,000	Constant	1,000	Constant	1,000	Constant
Track Processing Delay	0.001	0.0001	1	0.5	2	0.5
Max Simultaneous Tracks Processed	1,000	Constant	1,000	Constant	1,000	Constant
Communicate Tracks Delay	0.001	0.0001	1	0.5	2	0.5
Max Tracks Communicated at Once	1,000	Constant	1,000	Constant	1,000	Constant
Identification Inputs	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Identification Delay	2	0.5	4	0.5	6	1
Max Targets Simultaneously Identified	1,000	Constant	1,000	Constant	1,000	Constant
Threat Evaluation Inputs	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Priority 1% to MC	80	Constant	80	Constant	80	Constant
Priority 2% to MC	60	Constant	60	Constant	60	Constant
Priority 3% to MC	40	Constant	40	Constant	40	Constant
Priority 4% to MC	20	Constant	20	Constant	20	Constant
Threat Evaluation Delay	5	1	6	1	7	1.5
Weapons Pairing Inputs	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Delay for Weapons Pairing	1.5	0.2	2.5	0.4	3.5	0.6
Max Targets Paired at a Time	1	Constant	1	Constant	1	Constant
BDA Stage	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Time to Conduct BDA	0.5	0.01	0.5	0.01	0.5	0.01
Max Simultaneous BDA	1,000	Constant	1,000	Constant	1,000	Constant
Prob. Good BDA	0.9	Batch size=1	0.9	Batch size=1	0.9	Batch size=1

Table 12. Skin of the Ship Radar Preliminary Model Inputs

Radar detection heights were calculated using the equation $R_1 + R_2 = \sqrt{8/3 * R_{Earth} * h_1} + \sqrt{8/3 * R_{Earth} * h_2}$,[73] substituting R_{MS} (Range from Launch Site to Ship) for $R_1 + R_2$ and solving for h_2, the height of the missile gives the following equation:

$$h_2 = \frac{(R_{MS} - \sqrt{8/3 * R_{Earth} * h_1})^2}{{}^{8}\!/_{3} * R_{Earth}}$$

---

[73] Robert Harney, *Combat Systems*, Vol. 1, pp. 107-108.

Interceptor Inputs

For the initial round of simulations, the interceptor inputs were kept very basic. Forecasted, nominal values were used for the probability of kill for all interceptors. A time correction factor was added to the model. This factor accounts for the time a laser must be held on target to achieve a kill. For the railgun, it accounts for the ballistic trajectory. An assumption was made that the missile's control surfaces allowed it to fly a linear path so its time correction factor remained 1. The maximum engagement range did not change for the missile and railgun. However, to account for the increased attenuation from the weather in the most likely and worst case scenarios, the laser engagement range and height were both degraded. Table 13 shows the model inputs used for the three scenarios.

				Best Case		**Most Likely**		**Stressed**	
Interceptor Type	**Speed**	**Time Correction Factor**	**P(k)**	**Max Range (km)**	**Max Height (km)**	**Max Range (km)**	**Max Height (km)**	**Max Range (km)**	**Max Height (km)**
DE/Particle Beam	270,000 km/s	Add 10^-6 seconds	0.95	500	200	400	200	300	200
DE/Free Electron	300,000 km/s	Add 2 seconds	0.9	500	2,000	400	1,800	300	1,600
Missile	6 km/s	Multiply by 1 second	0.8	1,800	750	1,800	750	1,800	750
Missile	8 km/s	Multiply by 1 second	0.8	2,400	1,000	2,400	1,000	2,400	1,000
Railgun	8 km/s	Multiply by 1 second	0.8	2,200	1,000	2,200	1,000	2,200	1,000
Railgun	10 km/s	Multiply by 1.12 second	0.8	4,400	2,000	4,400	2,000	4,400	2,000

Table 13. Interceptor Preliminary Model Inputs

5.6.1.2 Programs Used

Modeling and simulation were performed using two different programs that were linked. Microsoft Excel was used to calculate the ballistic missile trajectories. The system model was created using Extend Version 6.0. The system model was linked to three separate Excel workbooks, one for each launch site, each containing six worksheets, one per target. The BM trajectories were used as inputs to the system model. Microsoft Excel was also used to record the outputs from the system model. Extend sent various data to the Excel worksheets using "Data Send" blocks.

5.6.1.3 Subcomponents

The main components of the entire system model are hierarchical blocks representing launch sites and the detect to engage sequence plus BDA. All of these blocks will be discussed in detail. Other components that can be seen in the highest level of the model are various “Data Send” blocks, system variable blocks, “Exit” blocks, and attribute blocks. Together, all of these blocks simulate a single ship performing BMD against three total launch sites and a varying number of missiles. Figure 34 shows the left half of the system model overview.

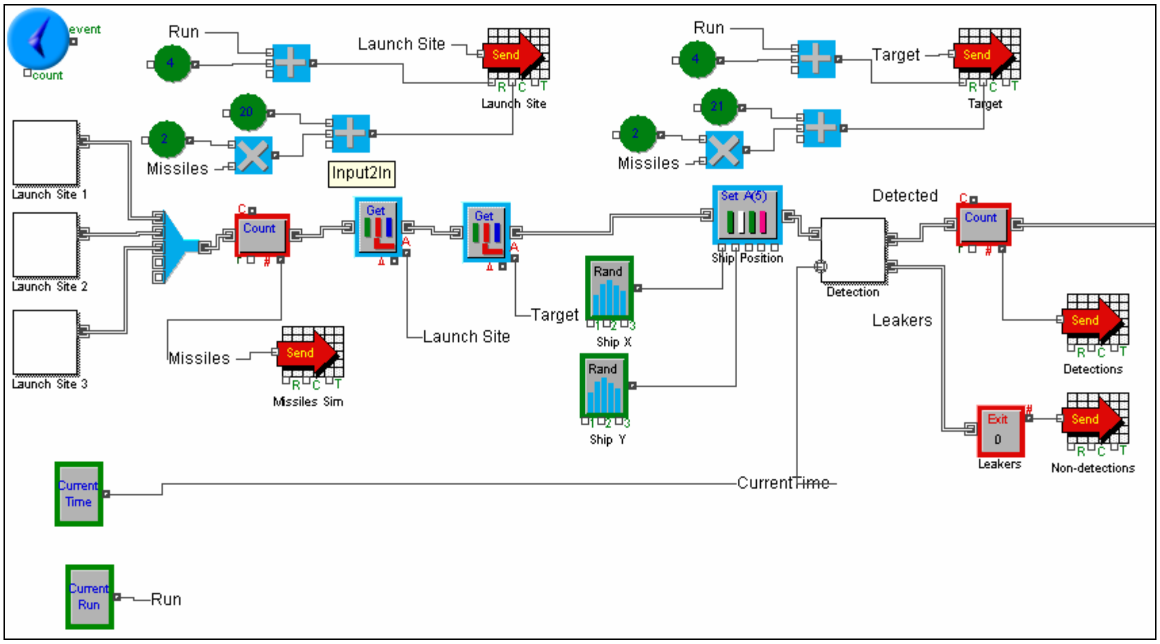


Figure 34. Extend Preliminary Model Overview Left Half

The first block in the top left corner of the model is an “Executive” block. One “Executive” block must be used for a discrete event model to act as a controller that allows the simulation to be ended at a set time or after a preset number of events. The blocks in the lower left corner are both “System Variable” blocks. One of these blocks inputs the system variable “CurrentTime,” which is the current simulation time. The other block inputs the system variable “CurrentRun,” which is the run number, which the simulation is currently going through. Both of these variables are used in various calculations throughout the model.

The next blocks in the simulation are “Launch Site” hierarchical blocks. There are three of these blocks, one representing each BM launch that was used for preliminary simulation. The blocks sent items into the system that have various attributes based on launch site and target. Once the items (missiles) enter the system they are combined to a single path using a “Combine (5)” block. Once the missiles are combined to a single path, they pass through a “Count Items” block. This block is used to count the number of missiles used for the simulation. This data is passed to an Excel spreadsheet using a "Data Send" block. The value of the "Count Items" block is passed to the connection name "Missiles" and is used in the calculation for the column number to send the data from the "Data Send" blocks for both launch site and target. These blocks are both at the top of Figure 34. The system variable "Current Run" is used to determine the proper column to which to send the data for launch site and target. The calculations to determine the proper row and column can be seen in the top of Figure 34. They are performed using system variables and constants as inputs to "Add" and "Multiply" blocks. The values sent to the Excel spreadsheet come from the "Get Attribute" blocks that follow the "Count Items" block. The first of these blocks contains the attribute "LaunchSite," which is passed to the "Data Send" block using a named connection. The second block passes the attribute "Target" to the "Data Send" block labeled "Target."

The next block in sequence is a "Set Attributes (5)" block. This block receives inputs from two "Input Random Number" blocks. The "Input Random Number" blocks both select an input from a real, uniform distribution. The numbers used for each of these distributions are based on a "steaming box" for the ship of 50 NM by 50 NM on the same grid used for launch site and target positions. The "Set Attributes (5)" block assigns the attributes "ShipX" and "ShipY," which are the x and y positions of the ship, respectively. These attributes remain constant throughout the simulation because the ship's movement relative to the movement of a BM was assumed to be irrelevant. Once the items pass through the "Set Attributes (5)" block, they enter the "Detection" hierarchical block. There are two exits from the "Detection" block. One passes items through a "Count Items" block to the tracking hierarchical block. The other sends nondetections to an "Exit" block. The number of items that exit through this block are sent to the output Excel sheet using a "Data Send" block and are considered leakers. The "Count Items" block is used to count the number of detections and is connected to a "Data Send" block to send the number of detections for each run to a Microsoft Excel spreadsheet.

The right half of the preliminary model overview is depicted in Figure 35. The flow of items through this section is fairly simple. "CurrentTime" is used in all of the hierarchical blocks for various calculations. Items first enter the "Tracking" hierarchical block. The “Tracking” block has two exits: one for successful tracks and one for handoffs. A handoff is determined using the attribute “TimetoEndofMC” and a decision block and can occur in any block from “Tracking” to “BDA.” All handoffs from these hierarchical blocks are combined to a single path using a “Combine (5)” block and a “Combine” block which leads to an “Exit” block. The number of items that enter this “Exit” block are sent to the output spreadsheet using a “Data Send” block. If an item is not deemed a hand off while inside the tracking block, it is passed to the “Identification” hierarchical block. The flow of items continues like this up to the “Engage” block. The “Engage” block has three exits. One exit is for handoffs. The other two exits are for the results of engagements as determined in the “Engage” hierarchical block. After the engagement block, the missiles pass through the “BDA” hierarchical block where they are either passed through to an exit, exit the system as handoffs, or are thrown back to the system using a “Throw” block.

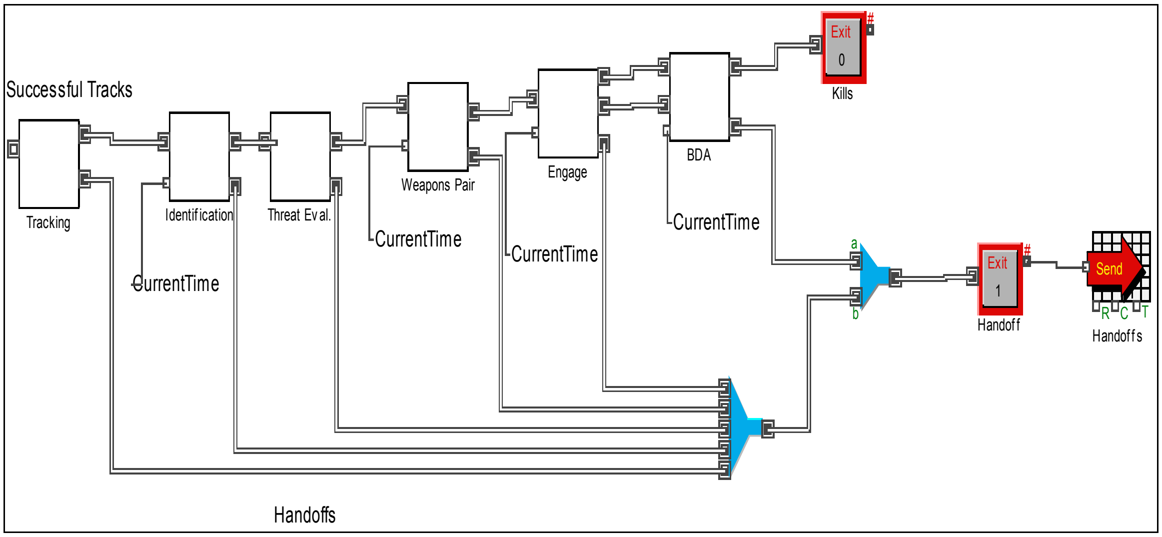
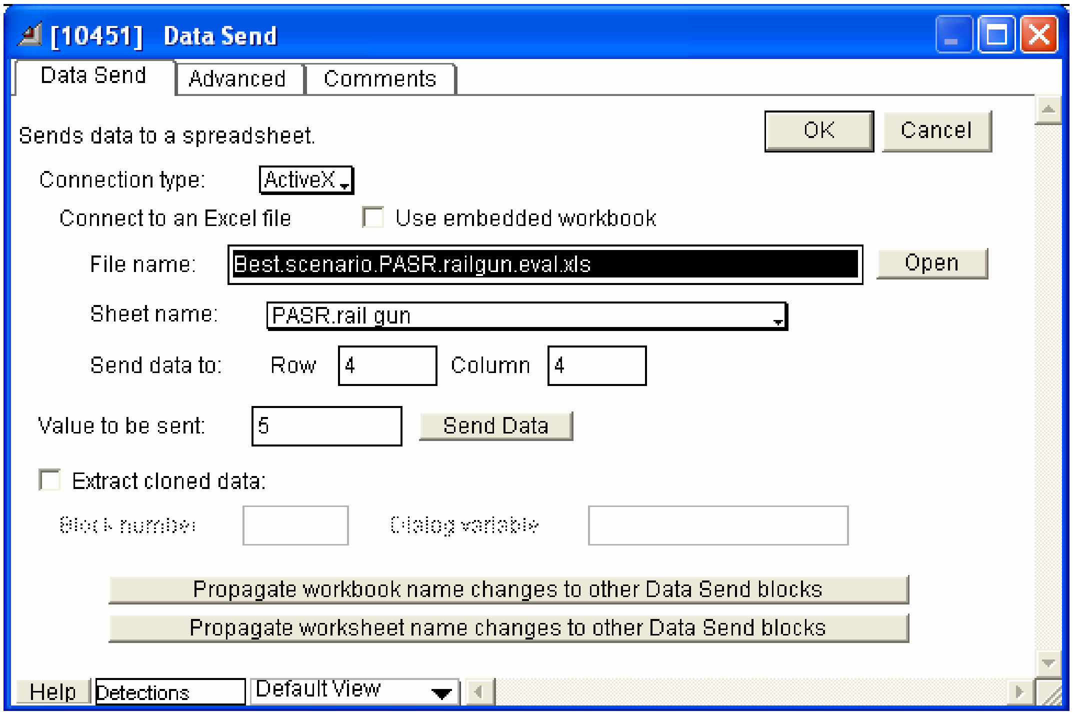


Figure 35. Extend Preliminary Model Overview Right Half

Figures 36 and 37 are both from the dialog of a “Data Send” block. Figure 35 shows the “Data Send” tab. As it can be seen from the dialog, the data is being sent to the Excel file titled “Bestscenario.PASR.railgun.eval.xls.” This sheet was used for all scenarios involving the railgun and renamed after the data for each architecture scenario was recorded. The second dialog shows the advanced settings tab. As shown in Figure 37, the value was sent to Excel only at the end of each run to improve the speed of processing each run. Also, the row the data was sent to was incremented every run because neither the run nor column connector were connected. The only exceptions to these settings are the "Data Send" blocks for launch site and target. These variables required a separate calculation to be made and the data to be sent immediately since multiple numbers were sent during each run.



Sends data to a spreadsheet.

Connection type: ActiveX

Connect to an Excel file ☐ Use embedded workbook

File name: Best.scenario.PASR.railgun.eval.xls

Sheet name: PASR.rail gun

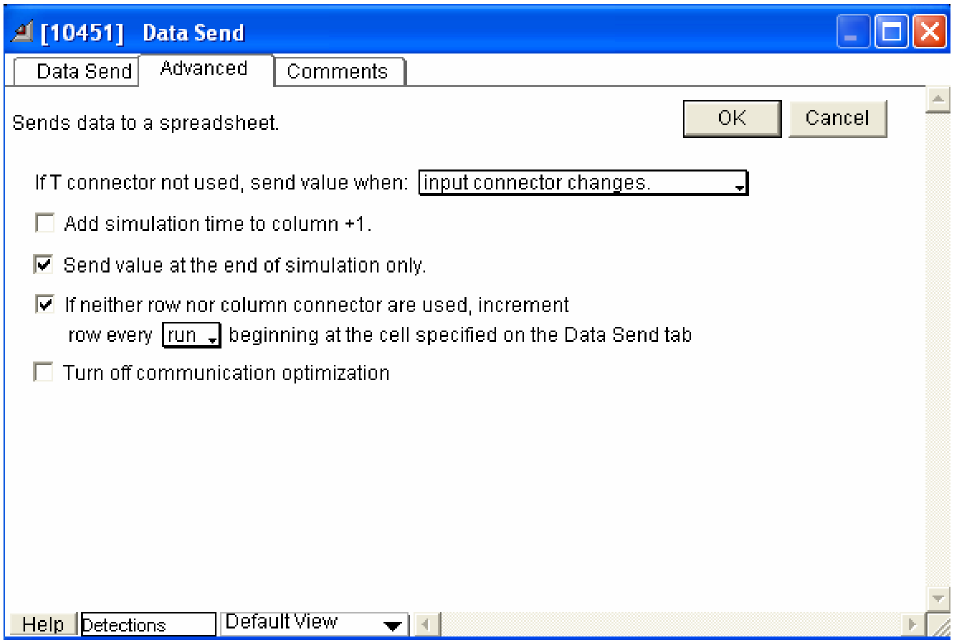
Send data to: Row 4 Column 4

Value to be sent: 5

☐ Extract cloned data:

Block number Dialog variable

Figure 36. Extend Preliminary Model Sample Data Send Block Dialog



Sends data to a spreadsheet.

If T connector not used, send value when: input connector changes.

☐ Add simulation time to column +1.

☑ Send value at the end of simulation only.

☑ If neither row nor column connector are used, increment row every run beginning at the cell specified on the Data Send tab

☐ Turn off communication optimization

Figure 37. Extend Preliminary Model Sample Data Send Block Dialog, Advanced Tab

5.6.1.3.1 Launch Site Hierarchical Blocks. For the preliminary system model there are three "Launch Site" blocks to account for the three launch sites used. The purpose of the "Launch Site" blocks is to insert items (missiles) into the system and randomly assign them a target. Figure 38 shows an overview of a Launch Site Hierarchical Block.

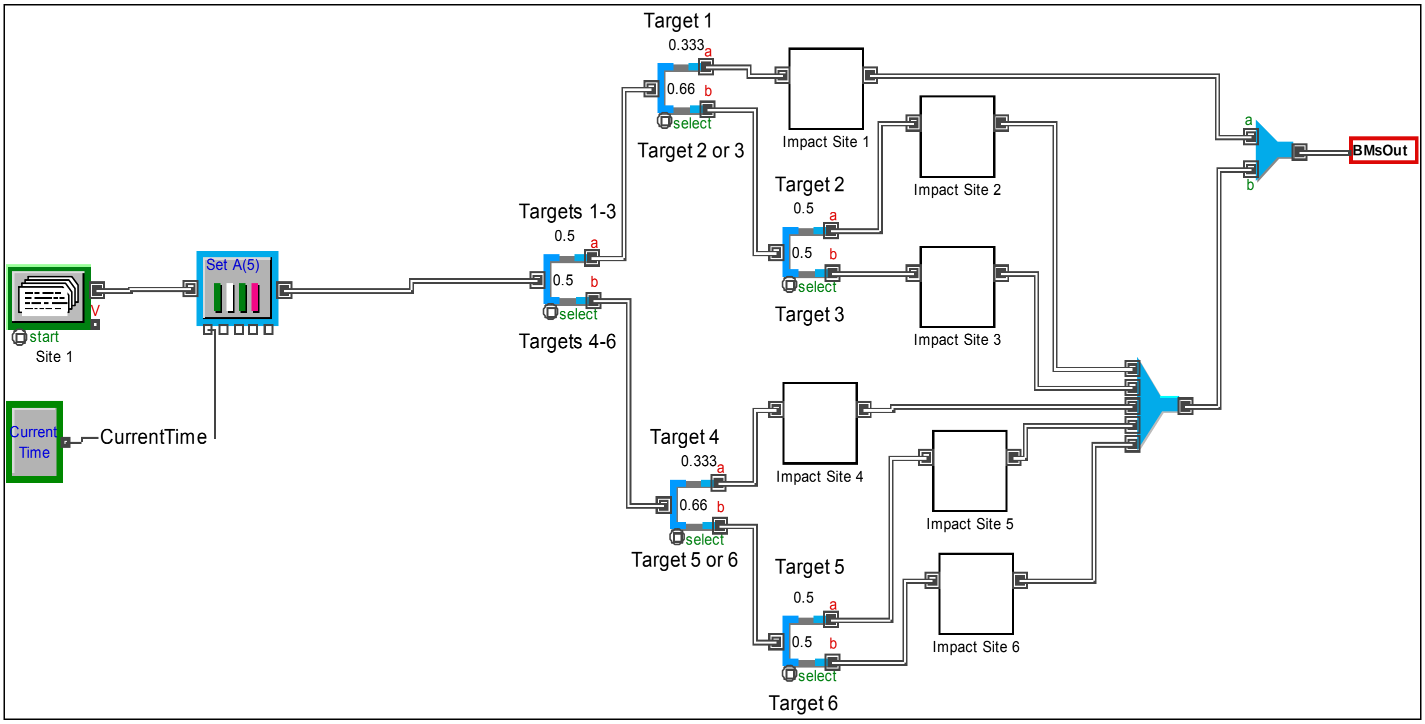


Figure 38. Extend Preliminary Model Launch Site Hierarchical Block

Items enter the system from the "Program" block. The number of missiles from the "Program" blocks varied with the three different scenarios. The only limitation of the block is that the missiles had to be launched at slightly different times or else they would all be assigned to the same target. After the initial launch, the missiles are assigned the attribute "LaunchTime" using the system variable "CurrentTime." "LaunchTime" is used to hold the time each individual missile is launched so this value can be used throughout the system model. Once a missile has been assigned its "LaunchTime," it passes through a series of "Select DE Output" blocks to establish the target toward which that particular missile is fired. For the preliminary system model, all targets had equal probability. Once the target is determined, the missiles are passed to the "Impact Site" hierarchical block that corresponds to that target. The "Impact Site" blocks inside the "Launch Site" blocks are slightly different than the one depicted in

Figure 34. They have one additional block that sets the attribute "Target" that is later used to send the missiles to the proper "Impact Site" hierarchical block. After being assigned the proper "Target" attribute and passing through the "Impact Site" block, the missiles are recombined into a single path and exit the "Launch Site" block.

Impact Sites Hierarchical Block

There are a total of 18 different "Impact Site" blocks. Each launch site/impact site block has a unique block. The purpose of the "Impact Site" blocks is to update the position of the missile based on the attribute "FlightTime." "Impact Site" blocks are located throughout the model, anywhere the missile position needs to be updated. Figure 39 shows an overview of an "Impact Site" block.

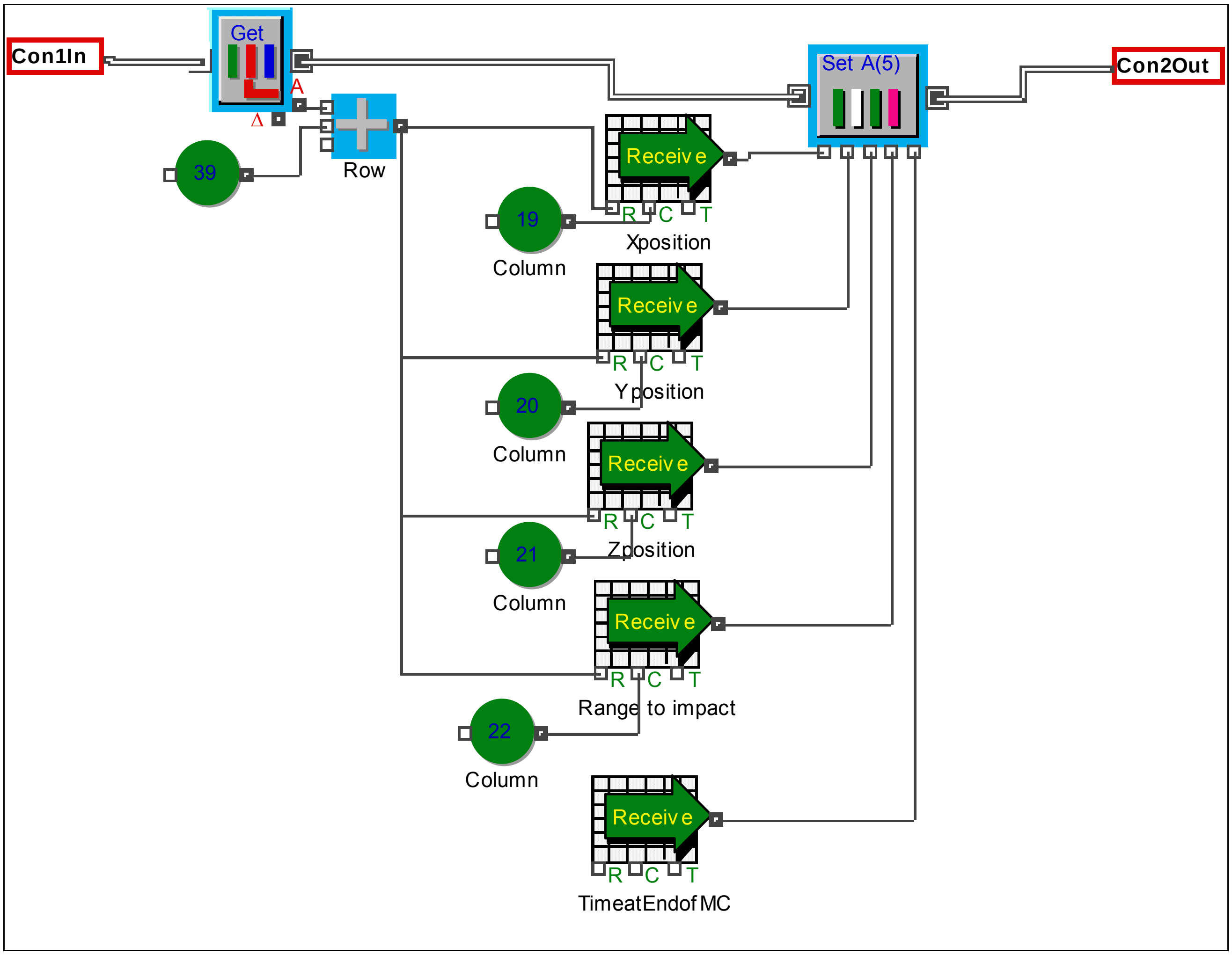
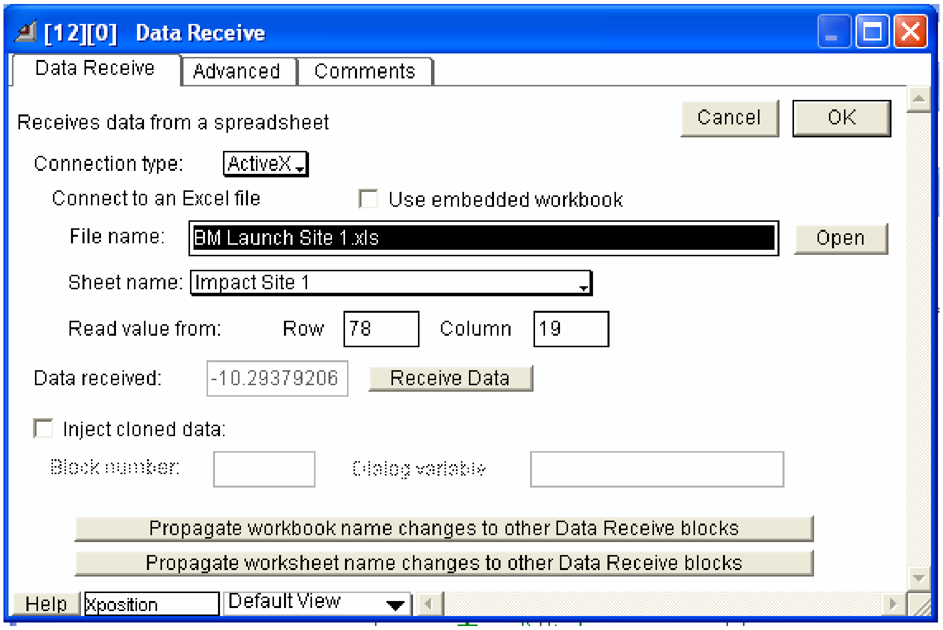


Figure 39. Extend Preliminary Model Impact Site Hierarchical Block

The first block in the "Impact Site" Block is a get attribute block that pulls out the attribute "FlightTime." The value of this attribute is then added to the constant 39 because in the Excel sheets, the data for the missile's position starts in row 39. After "FlightTime" is added to 39, the number is rounded to the nearest whole number automatically by the "Data Receive" blocks because there are only integer rows within Microsoft Excel. The column connector for each "Data Receive" block, other than the "TimetoEndofMC" block, tells the "Data Receive" block in which column to look. The "TimetoEndofMC Data Receive" block has the row and column inside the block since both remain constant throughout the entire time of flight of the missile. A sample "Data Receive" block dialog is shown in Figure 40. As can be seen from the dialog, the block is pulling data from the file "BM Launch Site 1.xls" and the worksheet "Impact Site 1." The file contains six separate worksheets for the corresponding six trajectories from launch site 1. Also shown in the dialog is the row and column from where the data came. The last time data was pulled from this sheet it came from row 79, column 19. Once the data is pulled from the Excel worksheets, it is assigned as attributes using a "Set Attributes (5)" block. After the attributes are set, the items are passed back to the hierarchical level above the "Impact Site" block.



[12][0] Data Receive

Receives data from a spreadsheet

Connection type: ActiveX

Connect to an Excel file

☐ Use embedded workbook

File name: BM Launch Site 1.xls

Sheet name: Impact Site 1

Read value from: Row 78 Column 19

Data received: -10.29379206

☐ Inject cloned data:

Block number:

Dialog variable

Figure 40. Extend Preliminary Model Sample Data Receive Block

5.6.1.3.2 Detection Hierarchical Block. The “Detection” hierarchical block receives items after they enter the system from the “Launch Site” hierarchical blocks. The purpose of this block is to model the time delays, radar range equations, and probabilities of detecting a BM. Figure 41 shows the left third of the “Detection” block.

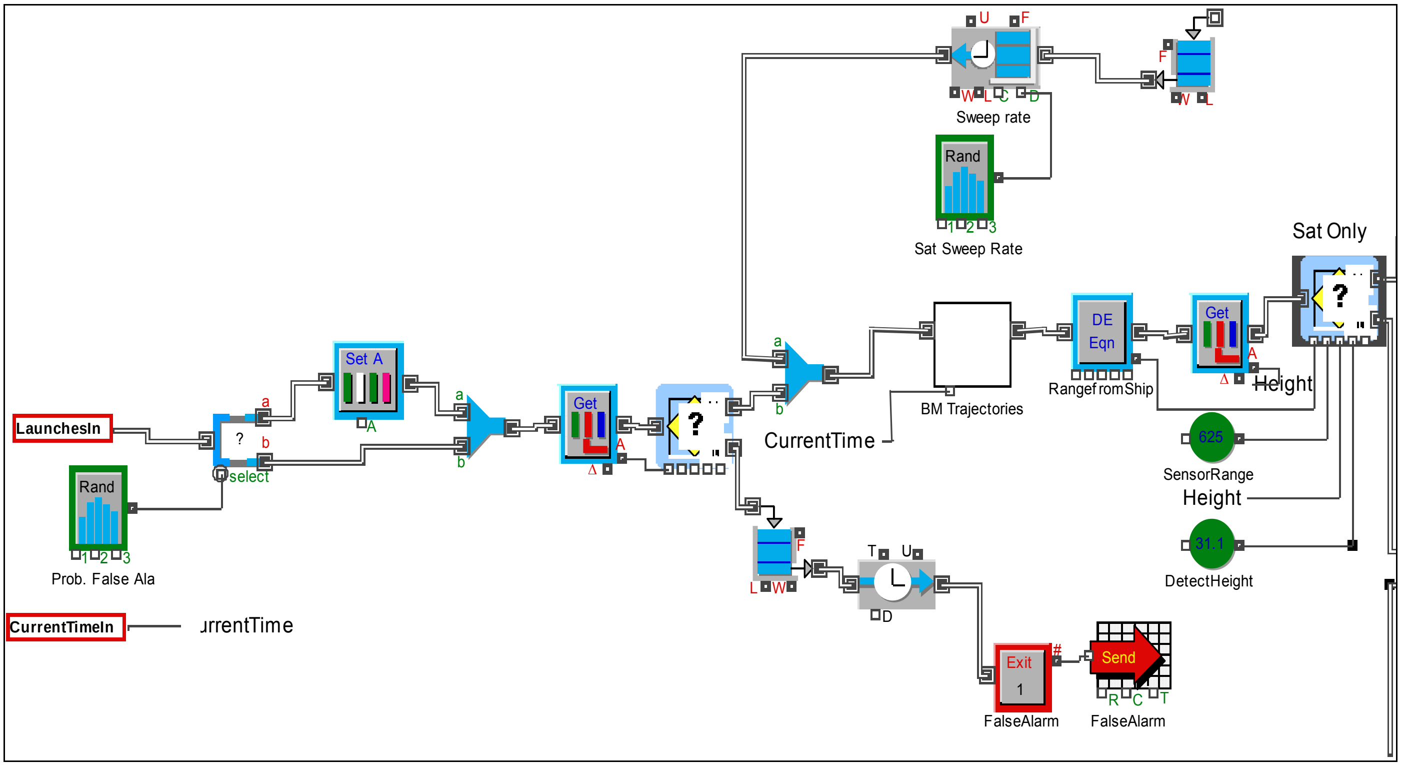
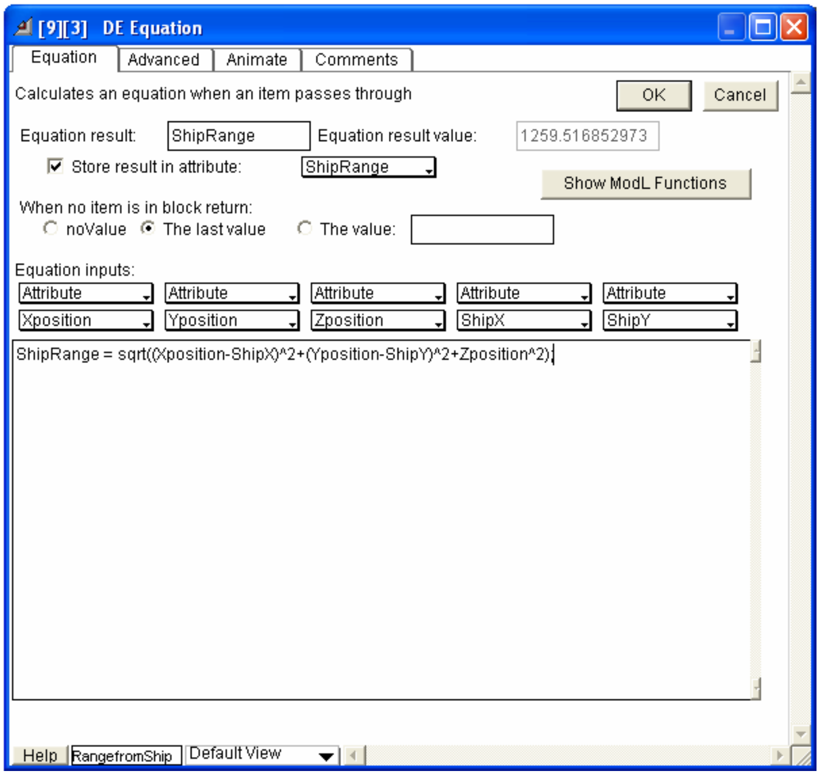


Figure 41. Extend Preliminary Model Detection Hierarchical Block Left Third

The first input to the “Detection” hierarchical block is missile launches. This input consists of the items that represent missiles. The other input is the system variable “CurrentTime,” which is used for various calculations and decisions. Once the items enter the “Detection” block, they pass through a “Select DE Output” block. This block splits the items between two paths based on the probability of false alarm. Items that are deemed false alarms based on the probability exit the “Select DE Output” block through output “a.” These items pass through a “Set Attribute” block that sets the attribute “False Alarm” to 1. Once this attribute is set, the items are combined using a “Combine” block. After the combine block, the items pass through a “Get Attribute” block to retrieve the value of “False Alarm.” This value is then passed to a “Decision (2)” block. The “Decision (2)” block uses the attribute “False Alarm” to determine which path to pass items through. Items that are deemed false alarms are passed to the "NoPath." These items then go through an "Activity" block to delay the system. These items then exit the system and the number is sent to the output data sheet. After the "Decision (2)" block, there is a combine block. This block joins the items from the "Decision (2)" block and items that pass through the loop for items that are not detected. This other path can be seen at the top of Figure 41. This path consists of a "Queue" block and an "Activity" block connected to a "Input Random Number" block. The "Activity" block represents the satellite's sweep rate. The input to the block is a normal distribution. The mean and standard deviation of this block were varied with scenario.

The next block in the linear sequence is a "BM Trajectories" hierarchical block. After the "BM Trajectories" block is a "DE Equation" block. This "DE Equation" block is shown in Figure 42. As can be seen in the figure, it is calculating "ShipRange," which is the distance from the ship to the missile, and assigning it as an attribute. The range is calculated using Pythagorean's theorem, assuming a linear path to the missile.



Calculates an equation when an item passes through

Equation result: ShipRange
Equation result value: 1259.516852973
☑ Store result in attribute: ShipRange

When no item is in block return:
○ noValue ● The last value ○ The value:

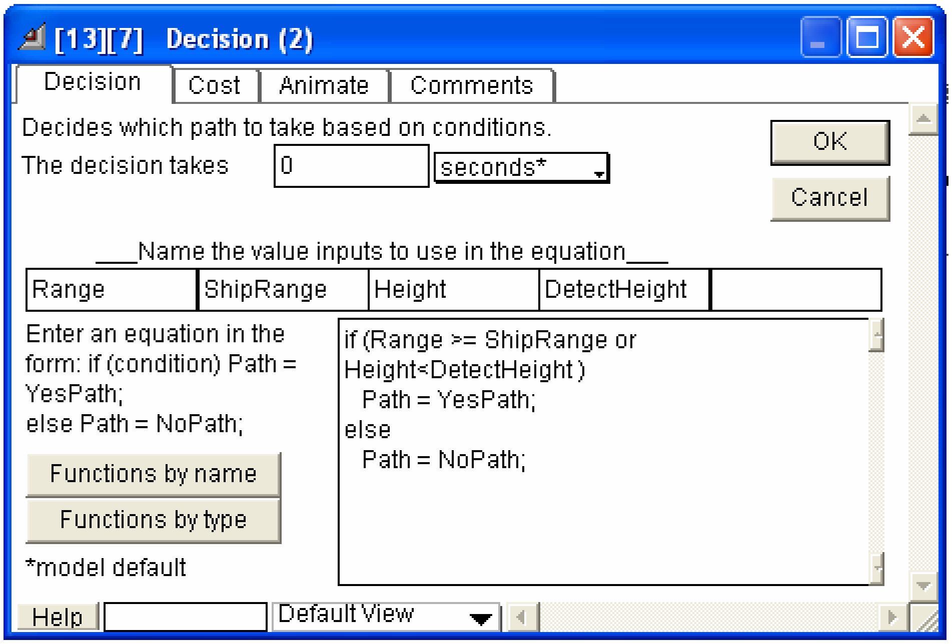
Equation inputs:

Attribute	Attribute	Attribute	Attribute	Attribute
Xposition	Yposition	Zposition	ShipX	ShipY

```
ShipRange = sqrt((Xposition-ShipX)^2+(Yposition-ShipY)^2+Zposition^2);
```

Figure 42. Extend Preliminary Model Range to Missile Calculation

After the range is calculated, the items pass through a "Get Attribute" block. This block gets the value of the attribute "Zposition," which is the height of the BM as calculated in the threat trajectory spreadsheets. After the "Get Attribute" block, the items are passed to a "Decision (2)" block. This "Decision (2)" block is shown on the right side of Figure 41 and the left side of Figure 44. This block determines whether the missile is within range of the ship's sensors or just the satellites. Inputs to this block include the range from the ship to the missile, height of the missile, maximum range, and detection height. Maximum range is based on the type of radar and scenario. Detection height is a constant based on using the radar range equation, at maximum range. If the missile is above the detection height and within the detection range it is passed to the ship's sensors. Otherwise, it is sent to the satellites to be detected. The dialog for the "Decision (2)" block for the sensor system is shown in Figure 43.



Decides which path to take based on conditions.

The decision takes 0 seconds*

___Name the value inputs to use in the equation___

Range	ShipRange	Height	DetectHeight	

Enter an equation in the form: if (condition) Path = YesPath;
else Path = NoPath;

```
if (Range >= ShipRange or
Height<DetectHeight )
  Path = YesPath;
else
  Path = NoPath;
```

*model default

Figure 43. Extend Preliminary Model within Ship's Radar Detection Decision Block

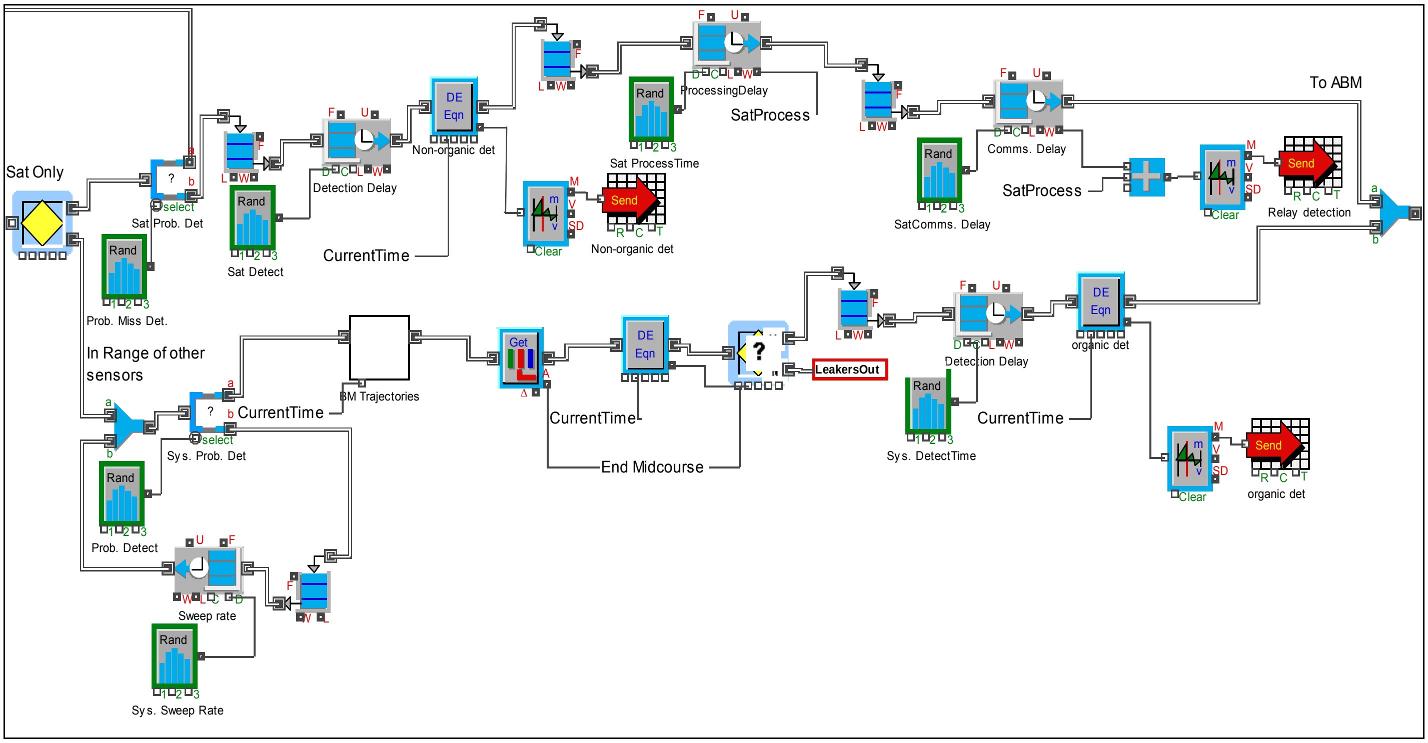
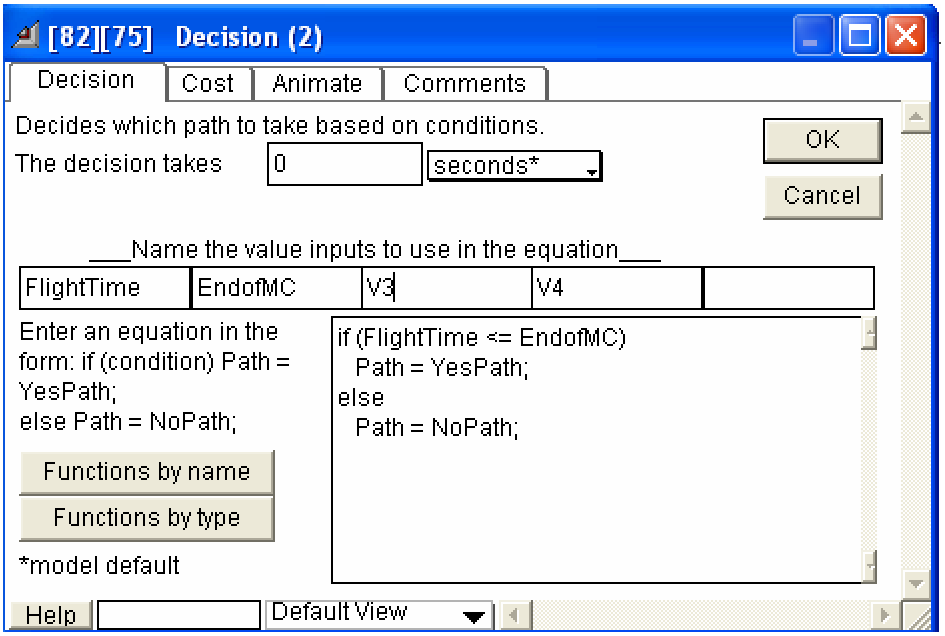


Figure 44. Extend Preliminary Model Detection Hierarchical Block Middle Third

The flow of items after the "Decision (2)" block is shown in Figure 44. As seen Figure 44, items that leave through the "Yes" path of the "Decision" block are passed to a "Select DE Output" block. This block determines whether the missile is detected by the satellites. It is based on the probability of a missed detection by the satellites. If an item is missed, it enters the loop that is shown in Figure 41, where it is delayed by the satellite's sweep rate. Once it is delays, it reenters the flow of items via a "Combine" block. If the missile is detected, it is passed to a "Queue FIFO" block before being passed to an "Activity, Multiple" block where time is increased based on the detection delay for the satellite. After the block is delayed, it enters a "DE Equation" block that determines the time from launch to detection for the satellite system and sends the results to a "Mean & Variance" block. This block calculates the mean satellite detection time and sends it to the data output sheet. The item then enters another "Queue FIFO" block before it goes through an "Activity, Multiple" block. This block delays the item to simulate the delay that would occur while the satellite is processing the detection. After the "Processing Delay" block, the items enter another queue before being passed to another "Activity, Multiple" block. This block is in place to simulate the delay that occurs while the satellites transmit the detections to the ship and other BMD assets. The results of the "Processing Delay" and "Comms. Delay" blocks are added and sent to a "Mean & Variance" block. The average of the results is sent to the data output sheet via a "Data Send" block. The items then enter the "Combine" block that can be seen on the right side of Figure 44 and the left side of Figure 46.

Items that exit the "Decision (2)" block through the "No" path are sent to the ship's sensors. They first pass through a "Combine" block, where they are combined with items that are not detected on a particular look. After the "Combine" block, the items pass through a "Select DE Output" block. This block routes items based on the ship's probability of detections. Items that are detected exit the block through path "a." Items that are not detected exit through path "b." Nondetections pass through a "Queue, FIFO" block and an "Activity, Multiple" block to account for the sweep rate of the ship's radar. After nondetections are delayed, they enter the "Combine" block seen on the left of Figure 44, where they are combined with items that have just entered the ship's detection range. If the items exit the "Select DE Output" block through the "a" path, they enter a "BM Trajectories" hierarchical block. After the "BM Trajectories" block, items pass through a "Get Attribute" block. This block retrieves the value of the attribute "EndofMC," which is the time from launch to the end of the BM's midcourse phase. The items then pass through a "DE Equation" block that calculates missile flight time. The values of "EndofMC" and "FlightTime" are both passed to a decision block. The "Decision (2)" block determines if the missile is still within the boost to midcourse phases as shown in Figure 45.



Decides which path to take based on conditions.

The decision takes 0 seconds*

___Name the value inputs to use in the equation___

FlightTime	EndofMC	V3	V4	

Enter an equation in the form: if (condition) Path = YesPath;
else Path = NoPath;

```
if (FlightTime <= EndofMC)
  Path = YesPath;
else
  Path = NoPath;
```

*model default

Figure 45. Extend Preliminary Model within Midcourse Decision Block

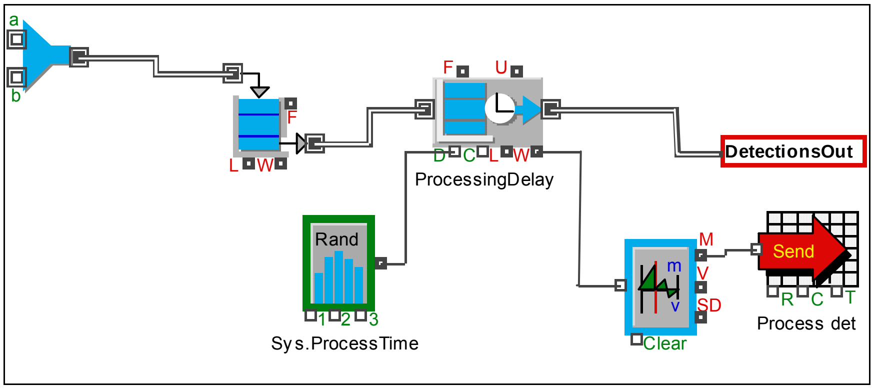


Figure 46. Extend Preliminary Model Detection Hierarchical Block Right Third

Figure 46 is the final third of the “Detection” Hierarchical block. The “Combine” block on the left side of the block is the same “Combine” block as the one on the right side of Figure 44. After the “Combine” block, the items enter a “Queue, FIFO” block before entering an “Activity, Multiple” block, where they are delayed. This delay is in place to account for the time it takes for the ship to process its own detections or those communicated from the satellites. The detection time is sent to a “Mean & Variance” block, where the mean is extracted and sent to the output sheet via a “Data Send” block. Once the data is sent, the items reenter the highest level of the model on the right side of the “Detection” block as seen in Figure 44.

BM Trajectories Hierarchical Block

The BM Trajectories Hierarchical Block was used in several places throughout the model. The purpose of the block is to divide the missiles based first on launch site and then on target to update the x, y, z positions of the BMs using the threat model Excel sheets. An overview of a "BM Trajectories" hierarchical block is shown in Figure 47. Figure 48 shows a sample "DE Equation" block.

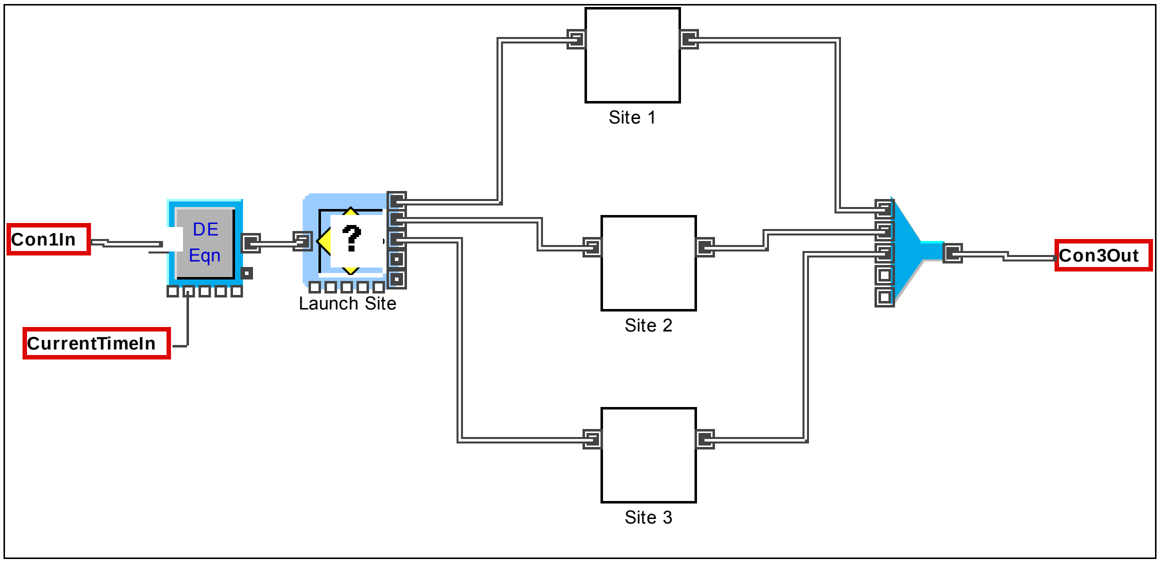
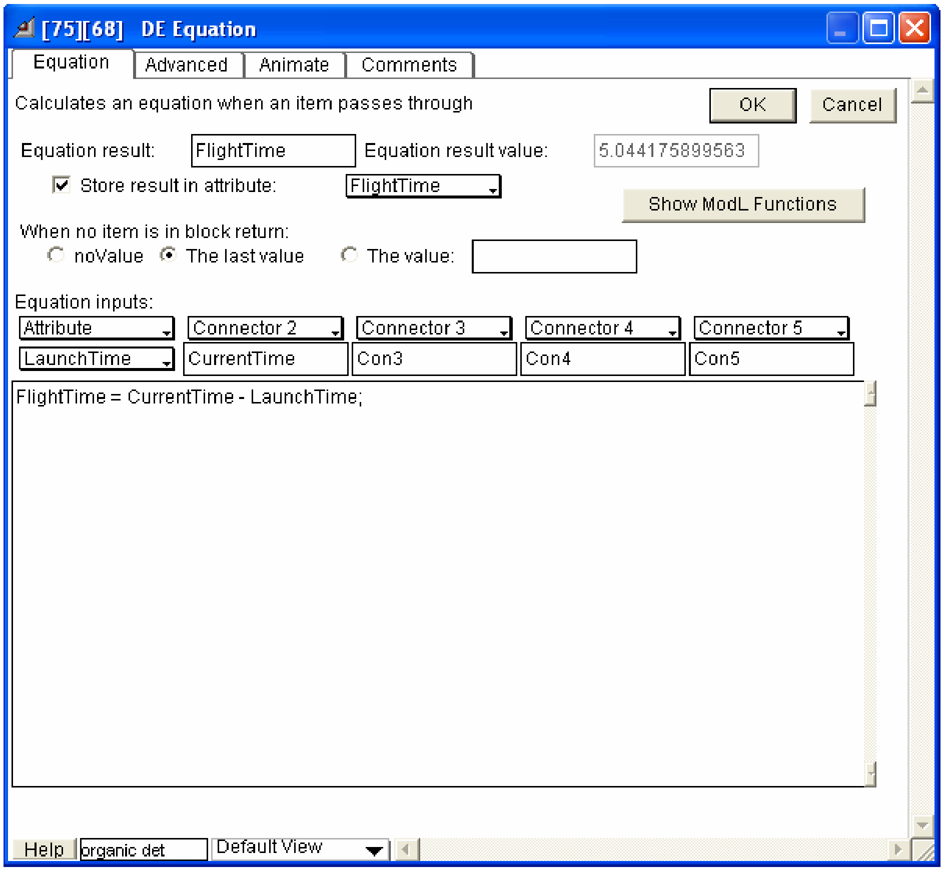


Figure 47. Extend Preliminary Model BM Trajectories Hierarchical Block



Calculates an equation when an item passes through

Equation result: FlightTime
Equation result value: 5.044175899563
☑ Store result in attribute: FlightTime

When no item is in block return:
○ noValue ● The last value ○ The value:

Equation inputs:

Attribute	Connector 2	Connector 3	Connector 4	Connector 5
LaunchTime	CurrentTime	Con3	Con4	Con5

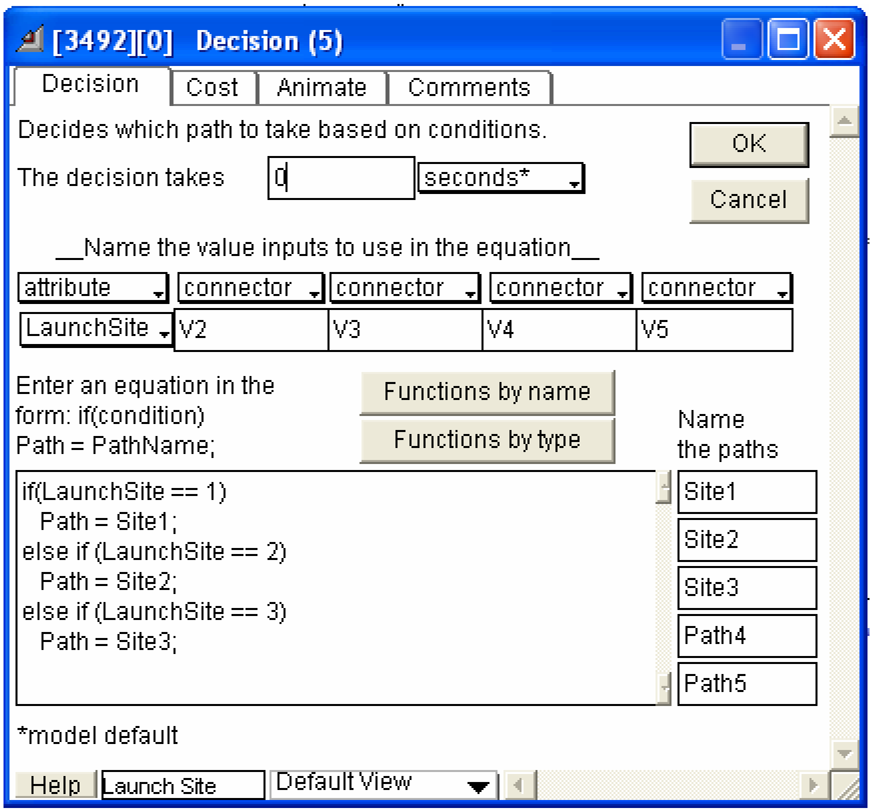
```
FlightTime = CurrentTime - LaunchTime;
```

organic det

Figure 48. Extend DE Equation Flight Time calculation

The first block in this hierarchical block is a “DE Equation” block that calculates the current time of flight of the BM using the missile’s launch time and current system time. As can be seen in Figure 48, “FlightTime” is the name given to the equation result and assigned as an attribute, which is calculated using the values “CurrentTime,” which is a system variable, and “LaunchTime,” which is assigned as an attribute in the “Launch Site” hierarchical blocks. The next block in the flow is a “Decision (5)” block, which is used to separate the missiles in order to send them to the proper “Site” hierarchical block. As is shown in Figure 49, the attribute “LaunchSite,” which is assigned upon missile launch, is used to correctly divide the missiles.

Once the missiles go through the “Site” hierarchical blocks, they are recombined into a single path and passed back to the hierarchical level above the “BM Trajectories” hierarchical block.



Decides which path to take based on conditions.

The decision takes 0 seconds*

__Name the value inputs to use in the equation__

attribute	connector	connector	connector	connector
LaunchSite	V2	V3	V4	V5

Enter an equation in the form: if(condition)
Path = PathName;

```
if(LaunchSite == 1)
  Path = Site1;
else if (LaunchSite == 2)
  Path = Site2;
else if (LaunchSite == 3)
  Path = Site3;
```

Name the paths

- Site1
- Site2
- Site3
- Path4
- Path5

*model default

Figure 49. Extend Decision (5) Block for Separating Missiles by Launch Site

Site Hierarchical Blocks

There are three site blocks, one for each launch site, in each "BM Trajectories" hierarchical block. The overall purpose of the "Site" block is to first split the missiles based on their impact site to properly update the missile position. An overview of a "Site" hierarchical block is shown in Figure 50.

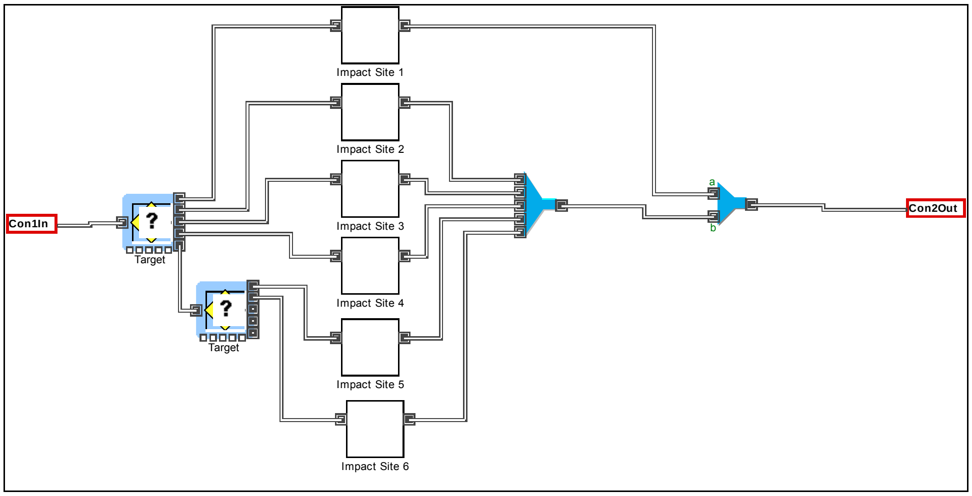


Figure 50. Extend Preliminary Model Launch Site Hierarchical Block

Objects are passed into the “Site” hierarchical blocks after being separated by launch site in the “BM Trajectories” hierarchical block. The two “Decision (5)” blocks are used to separate the missiles based on their impact site. The syntax is very similar to the “Decision (5)” block shown in Figure 50. In these blocks, the attribute “Target,” which is assigned upon missile launch, is utilized to separate the missiles. The next blocks are the “Impact Site” blocks. Once the missiles pass through the “Impact Site” blocks, they are recombined into a single path and passed back to the “BM Trajectories” block.

5.6.1.3.3 Tracking Hierarchical Block. The “Tracking” hierarchical block receives items that are deemed to be successfully detected by the “Detection” hierarchical block. The purpose of this block is to simulate the time delays and probabilities associated with establishing a successful track on a BM. Figure 51 shows the left half of the “Tracking” hierarchical block.

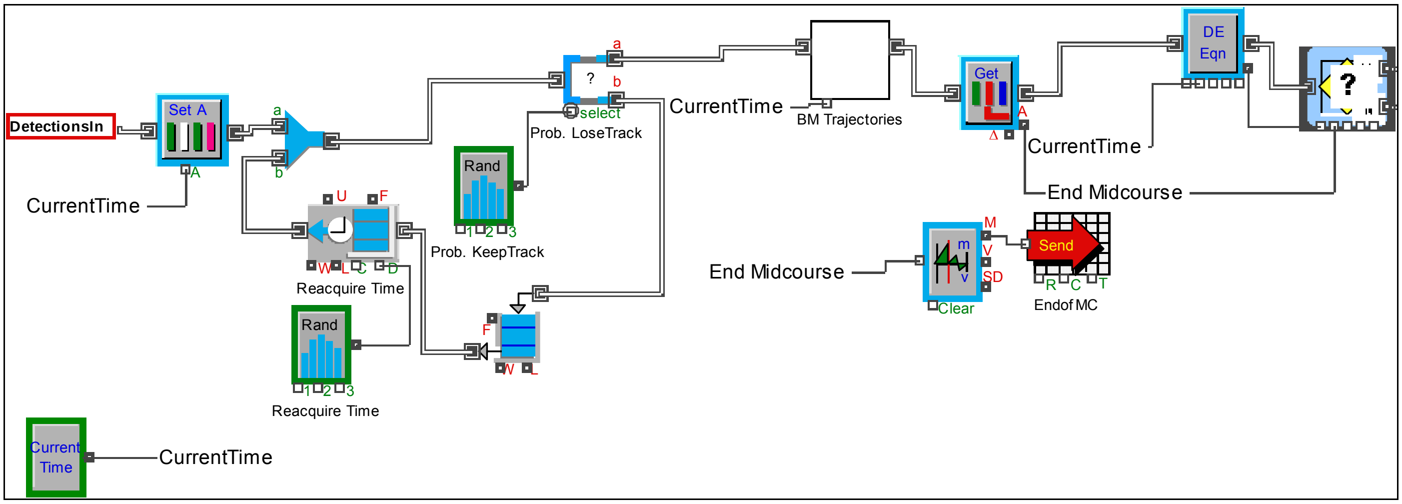


Figure 51. Extend Preliminary Model Tracking Hierarchical Block Left Half

Items that enter the “Tracking” hierarchical block have already been detected. The first block they pass through is a “Set Attribute” block. This block sets the attribute “DetectionTime,” which is later used to determine the time to formulate a track. After the “Set Attribute” block, items enter a “Combine” block. The “Combine” block merges these items with items that were determined to be lost tracks. The next block in sequence is a “Select DE Output” block. This block determines which items become dropped tracks. Dropped tracks enter a loop, where they pass through a “Queue, FIFO” block and an “Activity, Multiple” block. This loop is in place to simulate the time to reacquire a lost track. Tracks that are not lost enter a “BM Trajectories” hierarchical block, where the missile’s position is updated. After the “BM Trajectories” block, the items pass through a “Get Attribute” block.

This block retrieves the value of the attribute “EndofMC” and passes it to a “Decision (2)” block seen on the right side of Figure 51 and the left side of Figure 52. The next block in sequence is a “DE Equation” block, which updates the missile’s time of flight and stores its value in the attribute “FlightTime.” The result of this equation is also passed to the “Decision (2)” block seen on the right side of Figure 51 and the left side of Figure 52. The “Decision (2)” block determines whether the missiles are still within their boost to midcourse phase. The blocks seen at the bottom of Figure 51 are used to send the average time to end of midcourse to the data output sheet. The value of the attribute “EndofMC” is passed to the variable name “End Midcourse.” This value then enters a “Mean & Variance” block, which passes the value of mean to a “Data Send” block.

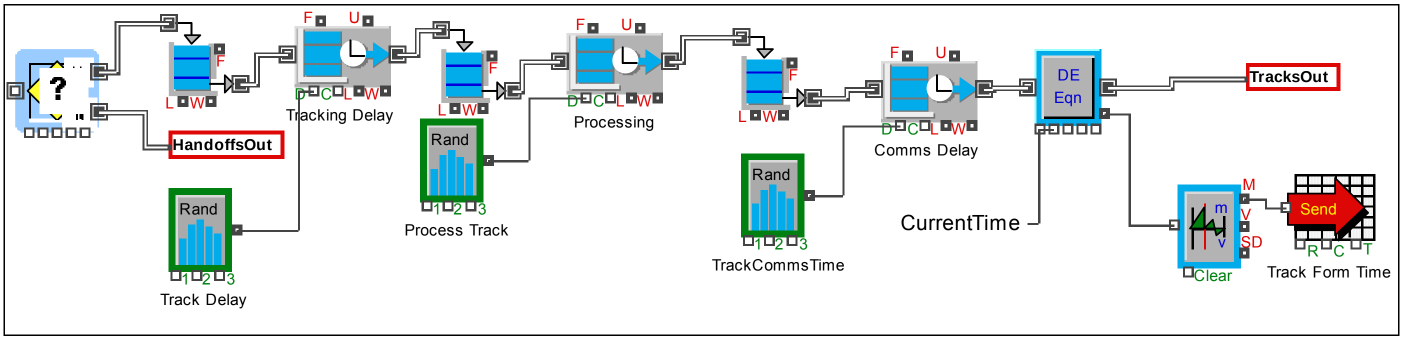


Figure 52. Extend Preliminary Model Tracking Hierarchical Block Right Half

The continuation of the tracking phase is seen in Figure 52. Items that are determined to be past the midcourse phase exit the “Tracking” block as handoffs. Items that still have not completed the midcourse phase enter a “Queue, FIFO” block. These items then pass through a series of “Activity, Multiple” and “Queue, FIFO” blocks. These blocks represent the delays associated with formulating a track, processing that track, and communicating the track to other assets. Once the items are delayed, the time to formulate a track is calculated based on the system time and the attribute “Detection Time.” This value is then sent to a “Mean & Variance” block, which passes the value to the data output sheet using a “Data Send” block. The items then leave the

“Tracking” block on the right side before entering the “Identification” hierarchical block as seen on the left side of Figure 52.

5.6.1.3.4 Identification Hierarchical Block. The “Identification” hierarchical block receives items that have already been established as tracks. The purpose of this block is to simulate the delay associated with identifying a track. Figure 53 shows the inside of the “Identification” block.

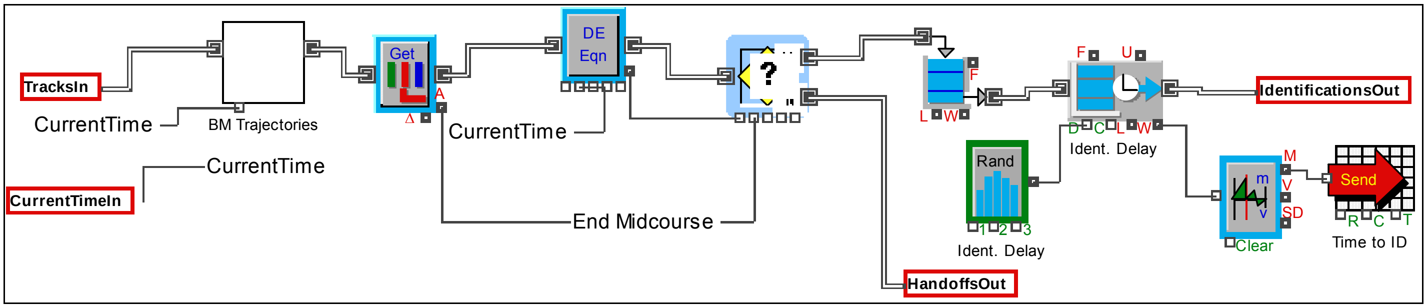


Figure 53. Extend Preliminary Model Identification Hierarchical Block

Items that enter the “Identification” hierarchical block have already been established as tracks. The first block these items pass through is a “BM Trajectories” hierarchical block, where the missile’s position is updated. The next block is a “Get Attribute” block that retrieves the value of the attribute “EndofMC” and passes this attribute to a “Decision (2)” block. The items then pass through a “DE Equation” block that updates the attribute “Flight Time” and passes its value to the “Decision (2)” block. The “Decision (2)” block determines whether these items have passed the midcourse phase. If the missile is past its midcourse phase, it exits the “Identification” hierarchical block as a handoff. Otherwise, it is passed to a “Queue, FIFO” block. After exiting the “Queue, FIFO” block, the items enters an “Activity, Multiple” block to delay the item, simulating the delay that occurs while identifying a track. The delay time is passed to a “Mean & Variance” block that passes the mean to a “Data Send” block, which sends the Identification delay to the data output sheet. After the time is incremented, the items exit the “Identification” block on the right side as seen in Figure 53.

5.6.1.3.5 Threat Evaluation Hierarchical Block**.** The “Threat Evaluation” hierarchical block receives items that have already been identified. The purpose of this block is to prioritize missiles based on the percentage of their boost through the midcourse phase they have completed. This prioritization is done assuming all targets are of equal value. Figure 54 shows the left half of the “Threat Evaluation” block.

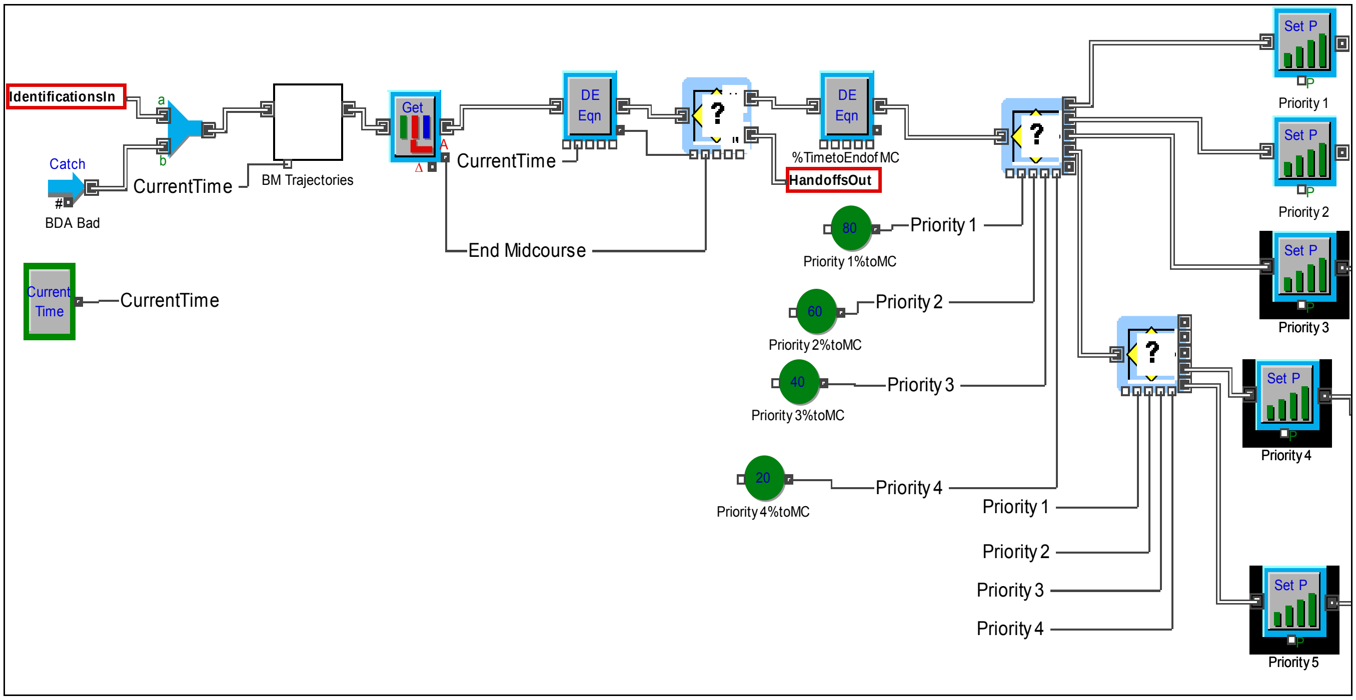
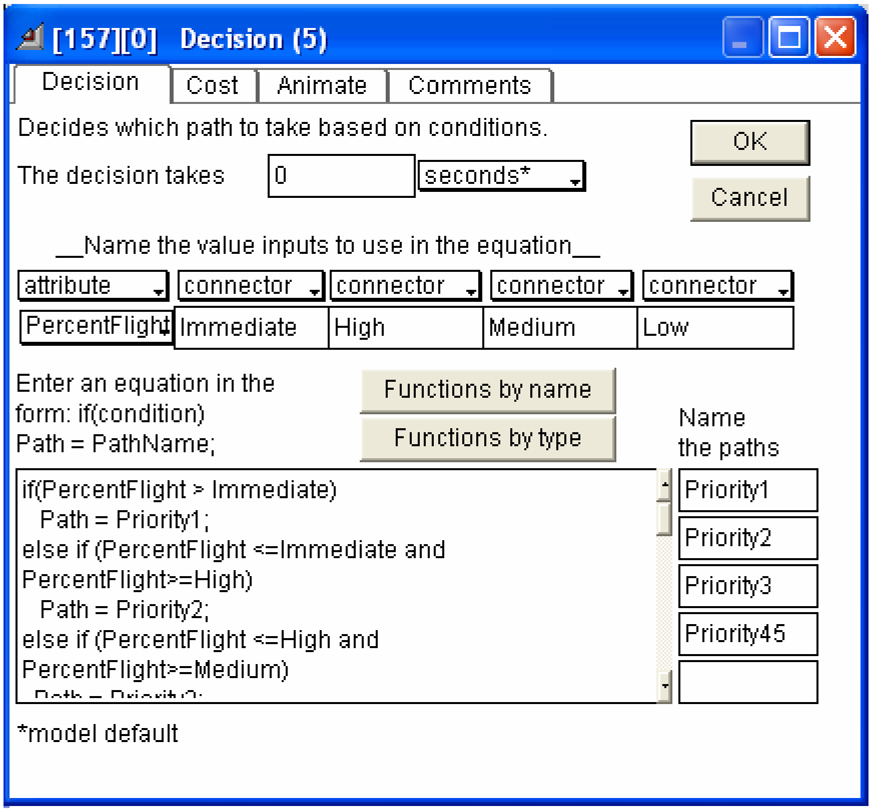


Figure 54. Extend Preliminary Model Threat Evaluation Hierarchical Block Left Half

Items that enter the “Threat Evaluation” block have already been identified. The first block these items pass through is a “Combine” block. This block merges items that have just been identified with items from a “Catch” block. The “Catch” block receives items from a “Throw” block that is in the “BDA” hierarchical block. The items that it receives are missiles whose BDA is unknown or bad. Items then pass through a “BM Trajectories” hierarchical block to update the missile’s position. Items then pass through the sequence of block to determine whether they have passed the midcourse phase. Items that have not completed the midcourse phase enter a “DE Equation” block. This block calculates the percentage of their path to the end of the midcourse that the missiles have completed. The next block in sequence is a “Decision (5)” block that separates items based on the percentage of the boost through midcourse phases the missile has completed. There are five priority levels broken into increments of 20%. For example, 20%-40% is a Priority 4. The dialog from the first “Decision (5)” block is shown in Figure 55. Two blocks were used rather than one because of the limited number of characters that can be typed into the dialog. Once items are split based on the percentage of their engagement window that they have completed, they pass through a set priority that establishes the priority from 1 to 5, depending on which path they follow. The items then enter the “Combine(5)” block seen on the left side of Figure 56.



[157][0] Decision (5)

Decision | Cost | Animate | Comments

Decides which path to take based on conditions.

The decision takes 0 seconds*

OK

Cancel

__Name the value inputs to use in the equation__

attribute	connector	connector	connector	connector
PercentFlight	Immediate	High	Medium	Low

Enter an equation in the form: if(condition) Path = PathName;

Functions by name

Functions by type

```
if(PercentFlight > Immediate)
  Path = Priority1;
else if (PercentFlight <=Immediate and
PercentFlight>=High)
  Path = Priority2;
else if (PercentFlight <=High and
PercentFlight>=Medium)
```

Name the paths

Priority1
Priority2
Priority3
Priority45

*model default

Figure 55. Extend Preliminary Model Prioritizing Block

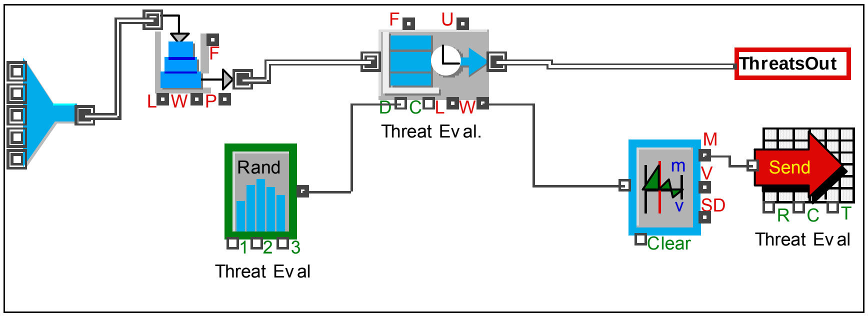


Figure 56. Extend Preliminary Model Threat Evaluation Hierarchical Block Right Half

After an item’s priority is set, they pass through a “Combine (5)” block to be merged into a single path. The next block items enter is a “Queue, Priority.” This block is similar to a “Queue, FIFO” block, except items with a higher priority or lower number jump to the front of the line. After the queue, items pass through an “Activity, Multiple” block to delay the items, simulating the time it takes to prioritize threats. The average threat evaluation time is sent to a “Mean & Variance” block that sends the mean to the data output sheet. Once the data is sent, the items exit the “Threat Evaluation” block on the right as can be seen in Figure 57.

5.6.1.3.6 Weapons Pairing Hierarchical Block. The “Weapons Pairing” hierarchical block receives items that have been prioritized. The purpose of the block is to simulate the delays that occur while pairing a threat with the proper weapon. Figure 57 shows the interior of the “Weapons Pairing” block.

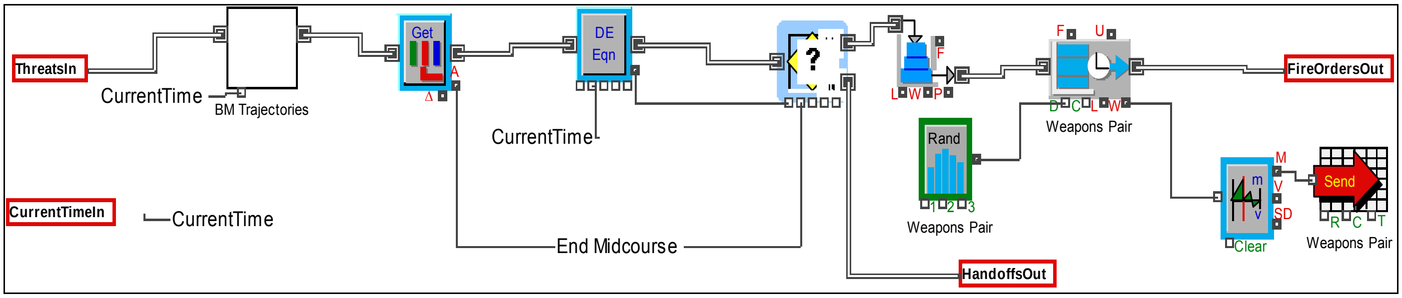


Figure 57. Extend Preliminary Model Weapons Pairing Hierarchical Block

Items enter the “Weapons Pairing” hierarchical block after passing through the “Threat Evaluation” block. The first few blocks they enter is the sequence of blocks that determines if the missile is still within the engagement window. Items that are deemed handoffs exit the block. Items that are still within the boost to midcourse phase enter a “Queue, Priority” block before entering an “Activity, Multiple” block. The “Activity, Multiple” block delays the items to account for the time that occurs while pairing a target with a weapon. The time delay is sent to a “Mean & Variance” block, which sends the mean to the output data sheet. Then, the items exit the “Threat Evaulation” block on the right, as can be seen in Figure 57.

5.6.1.3.7 Engagement Hierarchical Block. The “Engagement” hierarchical block receives items that have passed through the “Weapons Pairing” block. The purpose of this block is to simulate the delays and probabilities that occur for a BM engagement. Figure 58 shows the interior of the “Engagement” hierarchical block.

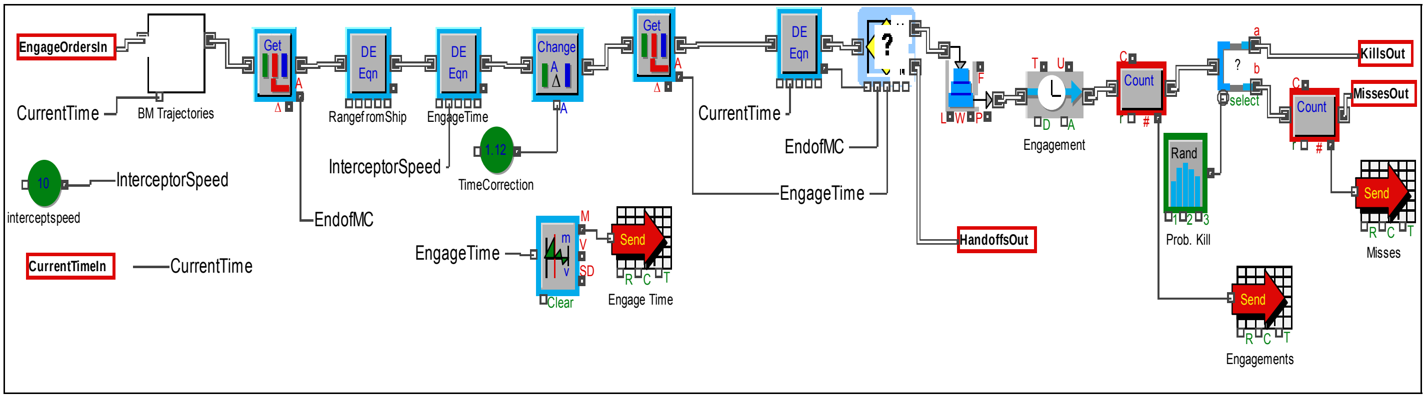
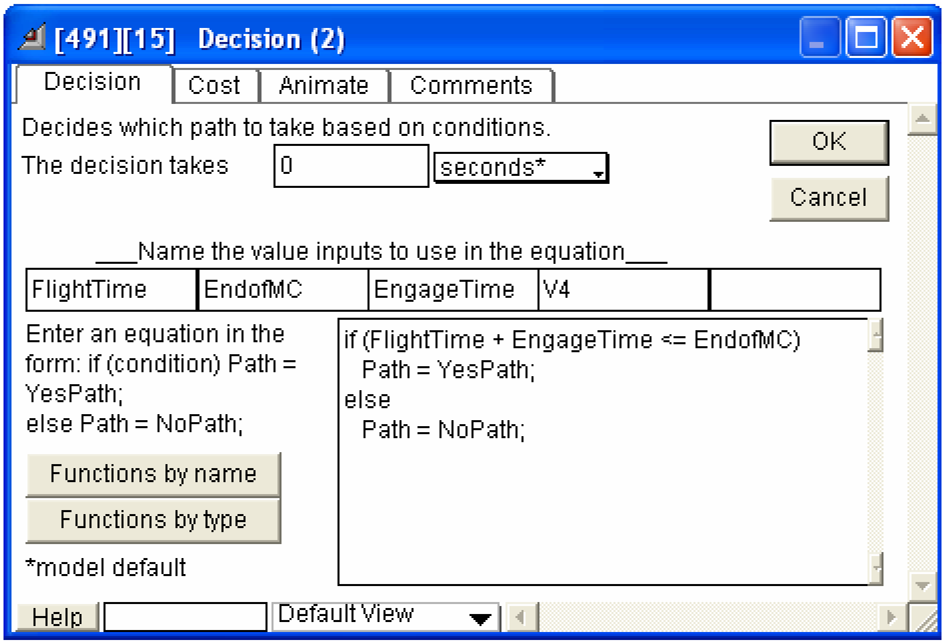


Figure 58. Extend Preliminary Model Engagement Hierarchical Block

As can be seen on the left side of Figure 58, there are three input blocks that feed into the blocks. From the bottom, the first input is the system variable "CurrentTime" is input to be used in various calculations. The next input is a "Constant" block representing the speed of the interceptor in kilometers per second. The top input is where the "Engagement" block receives items after they pass through the "Weapons Pairing" block. Once items enter the "Engagement" block, they enter a "BM Trajectories" block where the missile's position is updated based on the attribute "FlightTime." Following the "BM Trajectories" block is a "Get Attribute" block that retrieves the value of the attribute "EndofMC." The next block in sequence is a "DE Equation" block that calculates the range from the ship as seen in Figure 58. The next "DE Equation" block calculates the engagement time and assigns it as an attribute titled "EngageTime." The equation is a simple distance divided by speed calculation. Although the model would have been more accurate if the relative velocity of the interceptor and missile was used, the calculation would have added unnecessary complexity to the model and yielded minimal change. Missiles traveling away from the ship would have taken longer to intercept and those heading toward the ship would take less time. Since for half of the targets the missile was heading toward the ship, the average time would be somewhere in between. Therefore, it is safe to assume a simple distance over speed approximation.

After the engagement time is set, items pass through a "Change Attribute" block. The "Change Attribute" block changes the attribute "EngageTime." This attribute is changed to account for the ballistic trajectory of a railgun round or the time a directed energy weapon must remain on target. For the missile and railgun interceptors, the block is multiplicative. For the laser, it adds the time the laser must be held on the missile for a kill. After the "Change Attribute" block, items pass through a "DE Equation" block, which calculates the missile's flight time. The result of the equation and the value of the attribute "EndofMC" are passed to a "Decision (2)" block that determines whether the missile is still within the engagement window. This block is slightly different than the other "Decision (2)" blocks that determine whether items are still within midcourse. The dialog for the block is seen in Figure 59. Handoffs exit the block and subsequently exit the model.



[491][15] Decision (2)

Decides which path to take based on conditions.

The decision takes 0 seconds*

Name the value inputs to use in the equation

FlightTime	EndofMC	EngageTime	V4	

Enter an equation in the form: if (condition) Path = YesPath;
else Path = NoPath;

```
if (FlightTime + EngageTime <= EndofMC)
  Path = YesPath;
else
  Path = NoPath;
```

*model default

Figure 59. Extend Preliminary Model within Midcourse Decision Block Dialog

Missile's that are still within the engagement window are passed to a "Queue, Priority" block. The next block is an "Activity, Delay (Attributes)" block. This block delays the items based on the attribute "EngageTime." One problem with the block is that only one item can be delayed at a time so key performance indicators are likely worse than they really would be. However, since all architectures experienced the same conditions, the overall results were not affected. Once items have been delayed for the time it takes for an engagement, they pass through a "Count Items" block. This block counts the number of engagements and passes the data to a "Data Send" block, which sends the data to the output sheet. After the "Count Items" block, items enter a "Select DE Output" block. This block routes items based on a random number input representing probability of kill. Items that leave through output “a” exit the “Engagement” block on the top output and are considered kills. Items that exit through output “b” pass through a “Count Items” block. This block counts the number of failed engagements and passes the number to a “Data Send” block that sends the number to the data output sheet. After the “Count Items” block, these items exit the “Engagement” block through the middle output.

5.6.1.3.8 BDA Hierarchical Block. The “BDA” hierarchical block receives items that have been “engaged.” The purpose of this block is to simulate the delays and probabilities that occur while assessing the damage done to a target. Figure 60 shows the left half of the “BDA” hierarchical block.

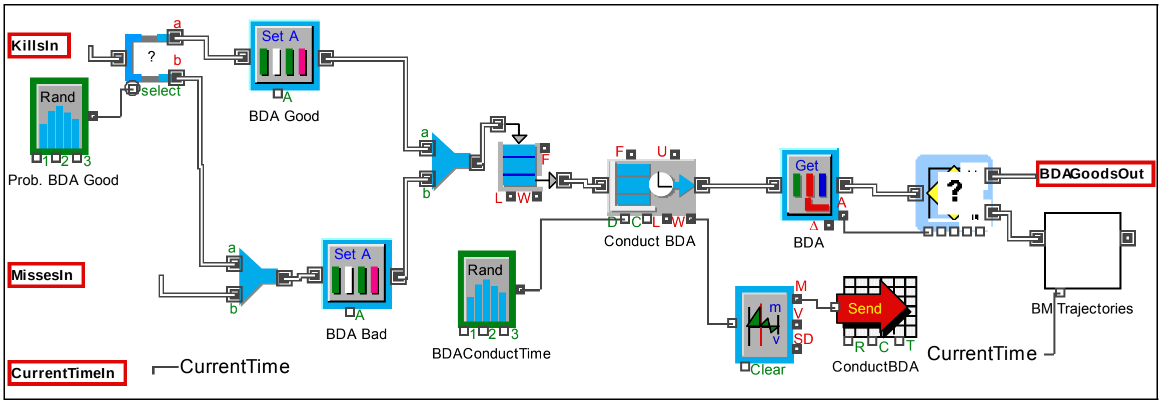
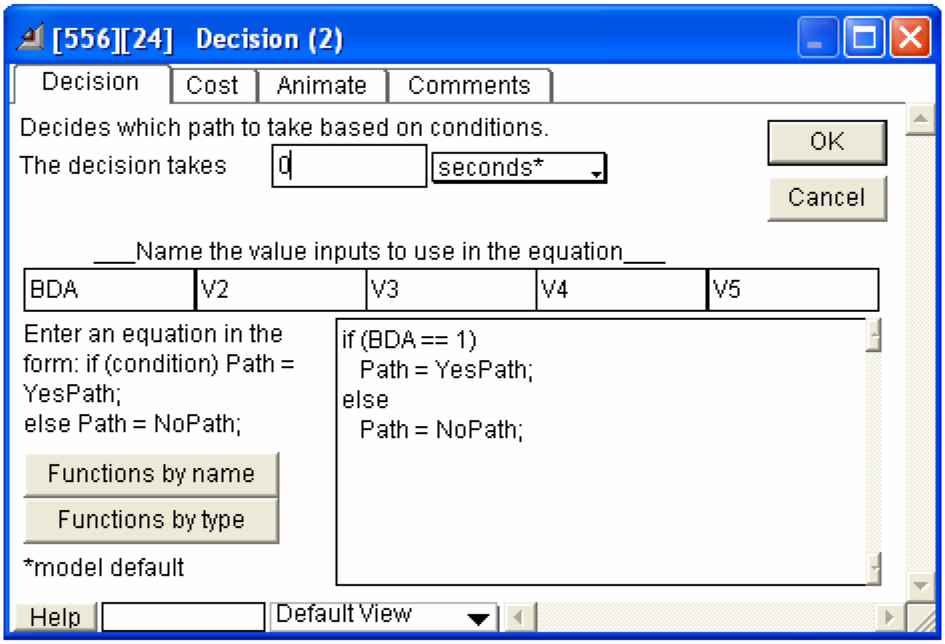


Figure 60. Extend Preliminary Model BDA Hierarchical Block Left Half

As can be seen in Figure 60, the “BDA” block receives three inputs. The first input is the current system time in the variable “CurrentTime.” The other two inputs are both item inputs that come from the “Engage” block as seen in Figure 59. The top input are missiles that have been determined to have been killed by the interceptor. These items then pass through a “Select DE Output” block. This block accounts for the probability that given a kill, the BDA will actually be good. A small percentage of the time, a BDA can be unknown. In this case, an unknown BDA is the same as a bad BDA, so these items get combined with items that have been deemed misses. Items that are considered kills and that leave output “a” from the “Select DE Output” block pass through a “Set Attribute” block. This block sets the attribute “BDA” to 1. Misses and kills that leave output “b” from the “Select DE Output” block are combined using a “Combine” block. These items then pass through a

"Set Attribute" block that sets the attribute "BDA" to 0. After the attribute "BDA" is set, the items are combined to a single path using a "Combine" block.

After the items are combined, they enter a "Queue, FIFO" block before entering an "Activity, Multiple" block. The "Activity, Multiple" block delays the items to account for the time it takes to conduct a BDA. The delay for each item is sent to a "Mean & Variance" block, which sends the mean to a "Data Send" block. The "Data Send" block sends the mean time to conduct BDA to the data output sheet. Once the item is delayed, it passes through a "Get Attribute" block. This block retrieves the value of the attribute "BDA" and passes its value to the "Decision (2)" block to its right, as seen in Figure 60. The "Decision (2)" block routes items based on the value of the attribute "BDA." The dialog for the block is seen in Figure 61.



Decides which path to take based on conditions.

The decision takes 0 seconds*

Name the value inputs to use in the equation

BDA	V2	V3	V4	V5

Enter an equation in the form: if (condition) Path = YesPath;
else Path = NoPath;

```
if (BDA == 1)
  Path = YesPath;
else
  Path = NoPath;
```

*model default

Figure 61. Extend Preliminary Model BDA Decision

As can be seen from the dialog, items whose "BDA" attribute is equal to 1 or the item was killed and the BDA is good leave through the "YesPath." These items then exit the block and subsequently the system. Items that leave through the "NoPath" are passed to a "BM Trajectories" block, where the missile's position is updated. The path of items through the "BDA" block is continued below in Figure 62.

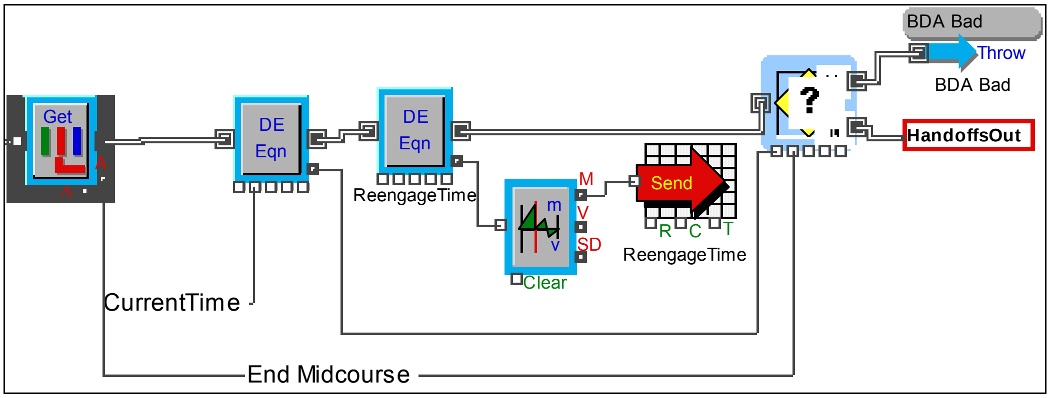
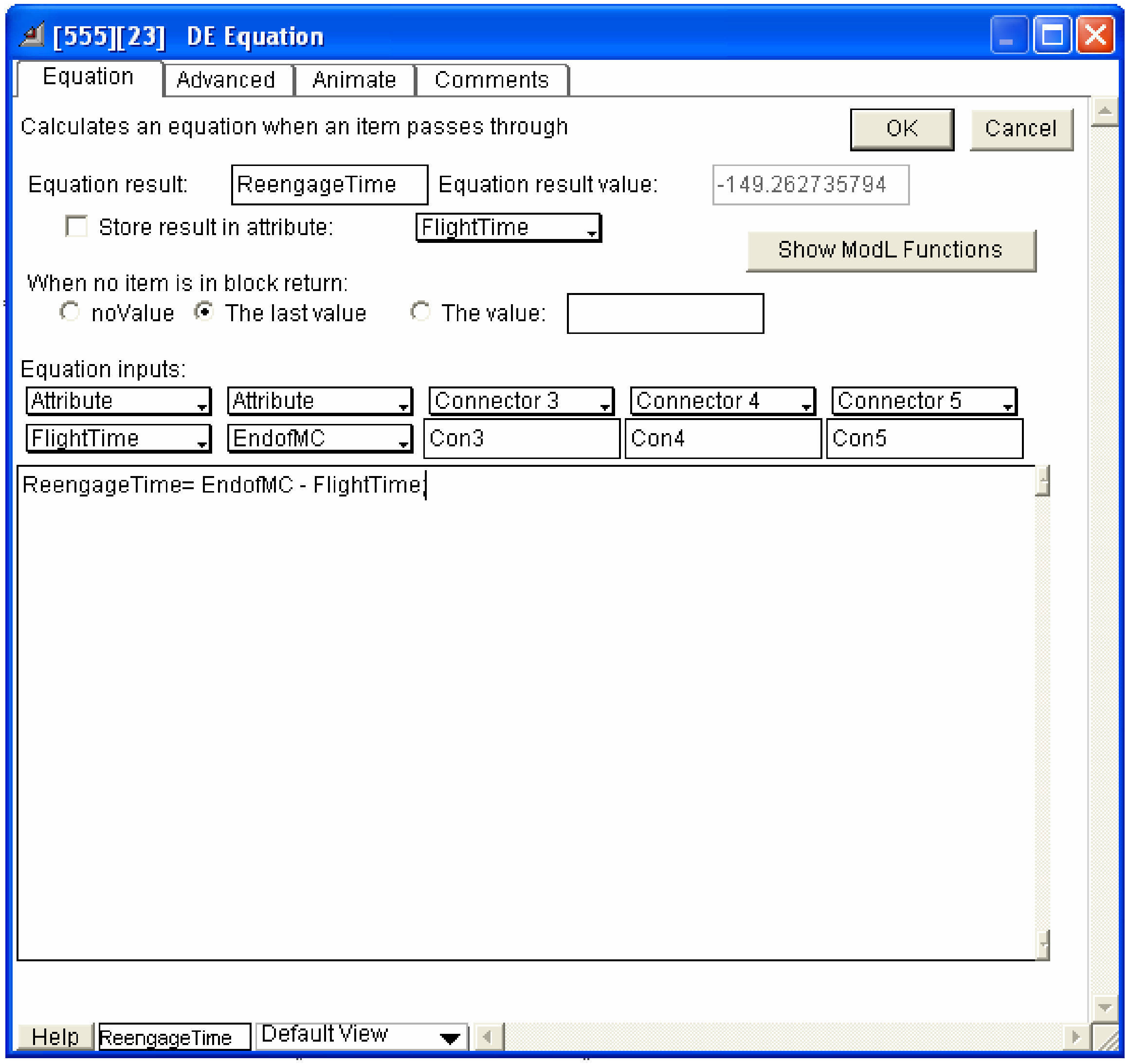


Figure 62. Extend Preliminary Model BDA Hierarchical Block Right Half

Items enter a “Get Attribute” block after passing through the “BM Trajectories” block seen in Figure 60. After this, the items pass through a “DE Equation” block that updates the attribute “FlightTime.” The next “DE Equation” block calculates the time left to reengage. Its dialog is seen in Figure 63. The result of this equation is sent to a “Mean & Variance” block that passes the mean to a “Data Send” block. The “Data Send” block sends the mean time to reengage to the data output sheet. After items exit the “DE Equation” block that calculates time to reengage, the items enter a “Decision (2)” block. The “Decision (2)” block determines if items are still within the engagement window. Items that are determined to be handoffs exit the “BDA” block and subsequently exit the system. Items that are still within the midcourse phase are sent to a “Throw” block. This block routes items without using a connector. This particular “Throw” block sends the items back to the “Catch” block in the “Threat Evaluation” block.



Calculates an equation when an item passes through

Equation result: ReengageTime

Equation result value: -149.262735794

☐ Store result in attribute: FlightTime

When no item is in block return:

○ noValue ● The last value ○ The value:

Equation inputs:

Attribute	Attribute	Connector 3	Connector 4	Connector 5
FlightTime	EndofMC	Con3	Con4	Con5

```
ReengageTime= EndofMC - FlightTime;
```

ReengageTime

Figure 63. Extend Preliminary Model Time to Reengage Calculation

5.6.1.4 Outputs

Microsoft Excel was used to record the outputs of the Extend system model. Data was sent directly from Extend to Excel using “Data Send” blocks. These blocks were very useful as they eliminated the need to copy and paste the data from Extend for the various attributes. Each basic architecture (i.e., missile with phased array radar) had its own output sheet. Once the results were recorded in Excel, the sheets were renamed to reflect the detailed architecture/scenario combination, including interceptor speed or type for the directed energy weapon.

Outputs from the system model included:

- Number of BM threats simulated
- Number of detections
- Number of nondetections
- Number of false alarms
- Number of handoffs
- Number of engagements
- Number of failed engagements
- Mean nonorganic time to detect
- Mean time delay in detection relay
- Mean time to process detection
- Mean organic detection time
- Mean track formulation time
- Mean time to ID
- Mean threat prioritization time
- Mean weapons pairing time
- Mean engagement time
- Mean weapons pairing time
- Mean time to conduct BDA
- Mean time to end of BM midcourse
- Launch site
- Target
- Mean time available for reengagement

These outputs were used to calculate several values of interest including:

- Probability of engagement given a detection
- Probability of kill given an engagement
- Probability of detection
- Probability of false alarm
- Probability of missed detection
- Probability of handoff

These values were used as system MOEs, along with mean engagement time and mean time available for reengagement.

5.6.1.5 Shortcomings

One of the major problems with the preliminary round of simulation is that no preferred system architecture was determined. The original purpose of the preliminary simulation was to choose a preferred system architecture. However, no radar stood out because all missiles were detected by nonorganic assets. This problem was resolved during the refinement of the system model. Another shortcoming of the preliminary model is that the detection height is based solely on the maximum detection range. In reality, this approximation would not be accurate. The actual height at which a missile would be detected would vary with range. This problem was also resolved in the refined system model. The next major problem with the simulation was that a spurious termination in Extend interrupted the simulation infrequently. Although this error did not affect the results, it slowed the simulation because a user had to click “Ok” to make the simulation continue.

There were two other shortcomings that were never resolved. First, there was no actual modeling of the sensor network. It was only modeled as a series of decisions, time delays, and probabilities. A more accurate representation would include modeling a sensor network as it would interact in reality, including the orbits of the satellite sensors. However, such a model never became readily available during the course of this project. Modeling the intercept suffered from the same shortcoming. It was modeled only as a probability of kill, velocity, maximum engagement range, and maximum engagement height.

5.6.1.6 Refinement Plan

In the next round of modeling, the shortcomings were fixed or attempted to be fixed. The first planned change to the model was to make the necessary changes to the inputs to essentially eliminate the nonorganic assets so a preferred radar could be selected. The next change that was planned for the system model was to add the calculation of the radar range equation based on the range of the ship to the missile to determine detection height. Another planned change to the system model was to make the necessary changes for multiple ships to operate together. Another planned refinement was to be able to input the ships, target, and launch site positions using latitude and longitude. Neither of these changes was made to the refined model; however, they were both added in some manner to the final system model. Modeling the interceptor and sensor network were also planned. However, neither of these was fully completed. The interceptor was never modeled, but rather a probability of kill per salvo was established to compare the missile and railgun systems.

5.6.1.7 Model Evolution

The system model originally started as a model for the commit stage. It consisted simply of a series of blocks representing the delays and probabilities associated with the detect to engage sequence. There were no inputs based on missile position. The original purpose of the model was to determine how fast an interceptor had to be in order to intercept the BM. After determining that this method would not work, the model slowly became an entire system model. The first step in its evolution was determining how to receive data from an Excel spreadsheet. This was done fairly easily using "Data Receive" blocks. After determining how to input data from Excel, scenarios were developed to use for BM trajectory calculations. Since the BM trajectory calculations were based on distance in kilometers, a grid had to be laid on a map containing launch site and target locations. The map can be seen in Figure 64. The launch sites are the red circles in the middle of the map. Targets are spread around the launch sites and represented by blue circles. The area represented in the map is a fictitious threat area. The diameter of the circle is 7,000 km and represents the maximum range of the threat missile. The target and launch site positions were determined using an x, y coordinate system. The target and launch site z positions or altitude have an insignificant impact on ballistic trajectory, so the heights were ignored.

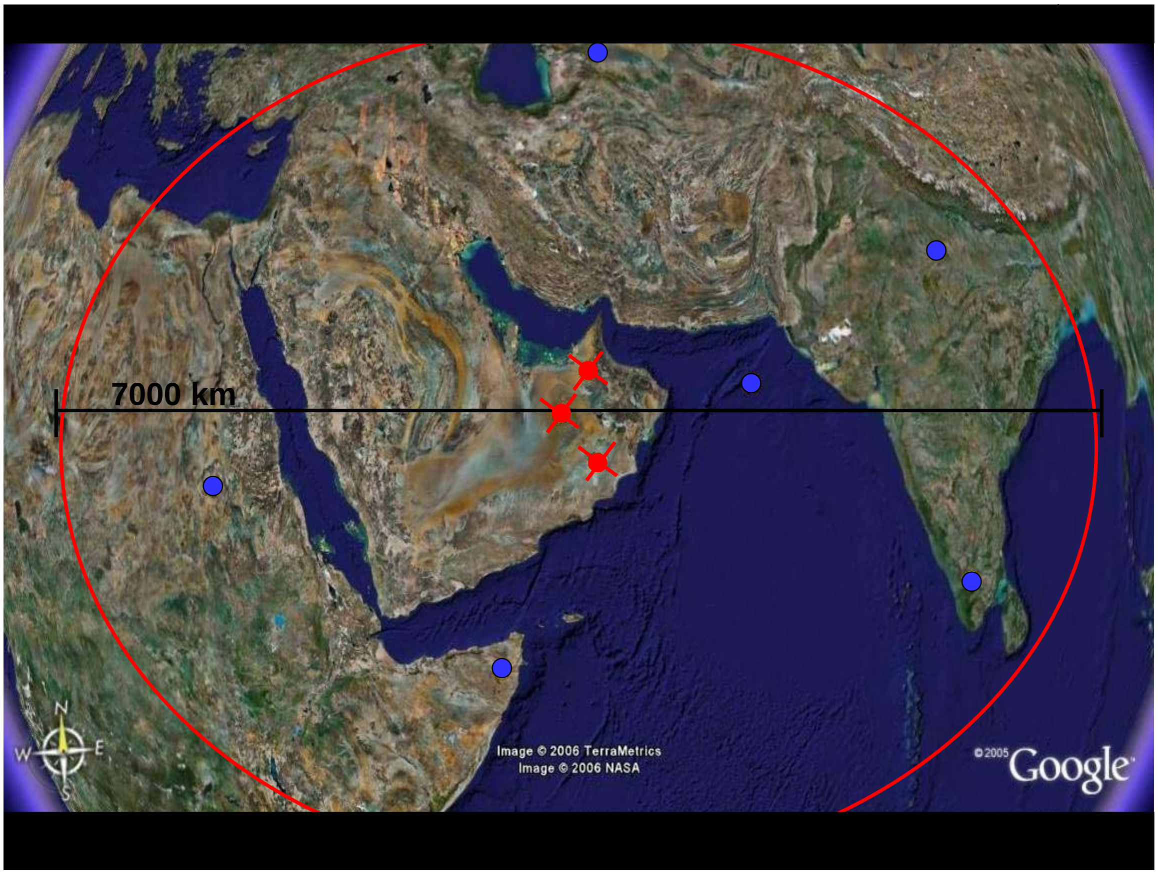


Figure 64. Google Earth Map of Launch Sites and Targets[74]

Each launch site was given its own Excel workbook with six sheets. The model was then linked to receive data from these sheets everywhere throughout that was necessary. Once Extend and Excel were linked, the single model evolved into six models, one for each architecture, to speed the simulation process. These six models were tested to make sure everything worked properly. After the debugging of the models were completed, the Notebook feature of Extend was utilized to make changing variables quick and easy. An Extend notebook is like a large dialog box containing any variable that is placed in it using the clone tool in Extend. Labels were added to keep variables straight. The boxes that are cloned are linked to the block in the Extend model so changing the value in the notebook changes a value in the block to which it is linked. The notebook feature was utilized to change the different variables as they were degraded from the best case scenario to the worst case scenario. The system model was further refined after the initial simulations.

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[74] Google Earth. Copyright 2006. Image modified (centered over Middle East) on 5 May 2006.

5.6.2 Preliminary Simulation Results

After the model was assembled and tested, it was ready for simulation and analysis, which was done iteratively. As more testing was done, more insights were gained from the simulations, which necessitated refinement of the models. It was not expected that the models would only be run through once and then testing would be done. The preferred architecture was expected to be selected after validation and three rounds of simulation and analysis. During the initial simulations, the directed energy alternatives were eliminated due to poor performance in the seven critical measures of performance. Tables 17 and 18 list the metrics and their results from the first 18 trials that became the eliminating factors for the directed energy alternatives.

In order to fully evaluate all of the architecture combinations in each of the scenarios, 36 trials were conducted. The run profile which enumerates the trial number and order that each architecture is run is depicted in Table 16. In order to achieve a high level of statistical confidence and mitigate any outliers or spurious results in the test, each trial completed 500 runs of the simulation. This is a total of 18,000 runs for the preliminary phase of simulation and analysis. An unexpected point of contention was the time needed to run all of the 36 trials. The problem came with running the more stressing scenarios. The best case trials ran rather quickly (only a few seconds per run) and the most likely scenario ran acceptably fast (approximately 30 seconds per run), but the worst case scenarios took anywhere from 5 to 9 hours per trial. In addition to its poor performance, this factored into the elimination of the directed energy alternatives from the worst case scenario testing with the skin-of-the-ship radar.

After 500 runs for each trial, the data was collected and analyzed in Excel spreadsheets.

# of BM threats simulated	# of BM failed engagements	Mean track formulation time (sec)	Mean time to conduct BDA (sec)
# of BM detections	Mean non-organic time to detect (sec)	Mean time to identify threat (sec)	Mean time for reengagement (sec)
# of BM nondetections	Mean time delay in detection relay (sec)	Mean threat prioritization time (sec)	Mean time to end of BM midcourse (sec)
# of BM false alarms	Mean time to process detection (sec)	Mean weapons pairing time (sec)	Launch Site
# of BM handoffs	Mean organic detect time(sec)	Mean interceptor engagement time (sec)	Target
# of BM engagements			

Table 14. Direct Outputs of the Extend System Model

The model's outputs were computed for each of the 500 runs within each of the 36 architecture-scenario trials. They were then used to compute the critical measures of performance as described in Figure 65.

Although many of the outputs were determined within the model, some were also fixed inputs to the model.

<u># of BM threats simulated</u> – Total number of threat missiles fired from any launch site to any location. This was a predetermined input to the model that varied by scenario.

<u># of BM detections</u> – Of the total number of threat missiles fired, this is the amount actually detected by the organic or inorganic sensors. This was calculated in Extend based on threat missile range and altitude from the ship and the radar's capability.

<u># of BM nondetections</u> – This is the complement to actual detections above. It is just the total detections subtracted from the total threat missiles fired.

<u># of BM false alarms</u> – This summed the per trial number of times a threat missile was falsely detected. It was an initial input to the model, entered in order to get a more realistic, less than optimal system performance.

<u># of BM handoffs</u> – A hand-off is the passing of firing responsibility onto an asset with higher probability of kill. This was determined through several phases of the Extend model. The model determined whether or not the interceptor could engage the threat missile once the radar had detected it. If the interceptor could not engage it or was able to engage it, but failed to intercept and destroy the threat missile, the model would consider this a handoff.

<u># of BM engagements</u> – This represented the number of times the interceptor was able to engage, but not necessarily destroy the threat missile after the radar detects the threat missile.

# of BM failed engagements – This metric summed the number of interceptors that engage the threat missile, but did not destroy it.

Mean nonorganic time to detect (sec) – Time after threat missile launch until the inorganic, satellite detection occurs. This is determined from the model for each trial.

Mean time delay in detection relay (sec) – This time accounts for the transmit time from the nonorganic detection entity to the engaging asset. It was also an input to the model. It is very small, but included for accuracy.

Mean time to process detection (sec) – Time for detecting asset to process detection data through onboard computer.

Mean organic detect time (sec) – Time after threat missile launch until the organic, shipboard detection occurs. This is determined from the model for each trial.

Mean track formulation time (sec) – Time to determine a track of threat missile after positive detection occurs. This was a varying input to the model.

Mean time to identify threat (sec) – Time to identify contact after detection and track is gained. This was also an input to the model.

Mean threat prioritization time (sec) – Time to queue contact with other hostile contacts to provide the best probability of kill once identification occurs. It was an input to the model.

Mean weapons pairing time (sec) – Time to determine and transmit to the asset with the highest probability of kill based on interceptor capability, asset location, and threat missile track. It was also an input to the model.

Mean interceptor engagement time (sec) – Interceptor time from launch to intercept or miss of the threat missile. This metric was calculated from the model based on time-distance equations.

Mean time to conduct BDA (sec) – Time after calculated intercept of threat missile and interceptor until battle damage assessment is determined. This was also an input to the model.

Mean time available for reengagement (sec) – This metric is determined by subtracting the detection through BDA output from the time to end of midcourse. It gives an insight as to whether the interceptor will have time to reengage or how much time will be left if handed off.

Mean time to end of BM midcourse (sec) – Time from threat missile launch until end of midcourse. This is determined in the threat missile model implemented in Excel and passed to Extend.

Launch Site – This identifies which of the three launch sites the threat missile is coming from. It was a random pick from the model as to which launch site would produce a threat missile.

Target – This identifies which of the six targets the threat missile is going to. This was also chosen at random from the model.

The model outputs were used either directly to evaluate the model or combined to make probabilities or critical time evaluations. In order to evaluate the competing architectures, seven critical MOPs were computed in order to distinguish the most feasible architecture of radar and weapon. These critical MOEs are listed in Table 15 and derived from the system outputs in Table 14.

Probability of engagement given a detection	P(engage | detection)
Probability of detection	P(detect)
Probability of kill given an engagement	P(kill | engagement)
Probability of false alarm	P(false alarm)
Probability of handoff given a detection	P(handoff | detection)
Time from detection to BDA	T (detect→BDA)
Time left to reengage after first cycle	T(reengage)

Table 15. Architecture Measures of Performance

In Figure 65 is the mathematical computation of the critical MOEs as determined in Excel.

$$P(Detect) = \frac{\sum Threat\_Missile\_Detections}{\sum Threat\_Missiles\_Launched}$$

$$P(Engage \mid Detection) = \frac{\sum Interceptor\_Engagements}{\sum Threat\_Missile\_Detections}$$

$$P(Kill \mid Engagement) = \frac{\sum Threat\_Missiles\_Destroyed}{\sum Threat\_Missiles\_Engaged}$$

$$P(False\_Alarm) = \frac{\sum False\_Alarms}{\sum Threat\_Missiles\_Launched}$$

$$P(Handoff \mid Detection) = \frac{\sum Handoffs}{\sum Threat\_Missiles\_Detected}$$

$$T(Detect \rightarrow BDA) = \sum \; All\ times\ between\ detect\ and\ BDA\ Assessment$$

$$T(\text{Reengage}) = T(End\_threat\_missile\_midcourse) - T(Detect \rightarrow BDA)$$

Figure 65. Derivation of Effectiveness Metrics

These metrics represent the top level performance specifications. The results of these parameters from the first iteration of simulations are graphically summarized in Figures 66 through 72. The graphs include information on each of the architectures for each of the scenarios for a particular critical measure of performance as denoted in the title of the graph.

In doing the simulations sequentially according to Table 16, analysis was able to be done after every group of six simulations were completed. Once all of the PASR simulations were completed, analysis of those determined the DEWs to be eliminated from the remaining SOTSR simulations. Each graph contains at least two architectures with no results, primarily the DEWs paired with the SOTSR. This is attributed to its poor performance and run times in the initial testing with the phased array radar. Barring all other results, the DEW interceptors achieved the results in Tables 17 and 18.

BEST case scenario	PASR	SOTSR
6 km/s Missile (M)	1	19
8 km/s Missile (M+)	2	20
8 km/s Railgun (R)	3	21
10 km/s Railgun (R+)	4	22
Particle Beam	5	23
Free Electron	6	24
MOST LIKELY scenario	**PASR**	**SOTSR**
6 km/s Missile (M)	7	25
8 km/s Missile (M+)	8	26
8 km/s Railgun (R)	9	27
10 km/s Railgun (R+)	10	28
Particle Beam	11	29
Free Electron	12	30
WORST case scenario	**PASR**	**SOTSR**
6 km/s Missile (M)	13	31
8 km/s Missile (M+)	14	32
8 km/s Railgun (R)	15	33
10 km/s Railgun (R+)	16	34
Particle Beam	17	35
Free Electron	18	36

Table 16. Preliminary Simulation Run Profile

Particle Beam	BEST	MOST LIKELY
P (engage)	0.0547	0.0185
Max Engagement Range	500 km	500 km
Max Engagement Height	200 km	200 km

Table 17. Particle Beam Eliminating Simulation Results

Free Electron	BEST	MOST LIKELY
P (engage)	0.0535	0.0234
Max Engagement Range	500 km	500 km
Max Engagement Height	2,000 km	2,000 km

Table 18. Free Electron Eliminating Simulation Results

The poor performance of the DEWs was directly related to their short lethal ranges. The DEWs' lack of ability to engage the threat made it an infeasible alternative for BMD and was therefore eliminated from any further testing since probability of engagement for the each weapon type is independent of radar. Table 19 defines the legend of symbols and abbreviations used in the MOE graphs in Figures 66 through 72.

M	6 km/s Missile Interceptor
M+	8 km/s Missile Interceptor
R	8 km/s Railgun Interceptor
R+	10 km/s Railgun Interceptor
PB	Particle Beam DEW
FE	Free Electron DEW
PASR	Phased Array Shipboard Radar
SOTSR	Ship-of-the-Ship Radar

Table 19. Graph Subscript Key

Probability of engagement given a detection, Figure 66, evaluates the ability of each weapon system to engage the threat missile once the radar detects it. These preliminary results were only partially beneficial. In one respect, they showed that the directed energy alternatives were poor performers in terms of their ability to engage the threat missiles; conversely, it did not provide a breakout between the other interceptor alternatives. The poor performance of the DEWs lead to the elimination of these interceptors from further testing. Engaging the threat missiles less than 5% of the time is infeasible and does not meet specification. Further testing will be done to yield definitive results between the railgun and missile alternatives. A breakout in probability of engagement for the weapon systems should follow a breakout in probability of detection for the radars. If the SOTSR detects the threat missile from a greater range, it should follow that the interceptors with the greatest range will have a higher probability of engagement.

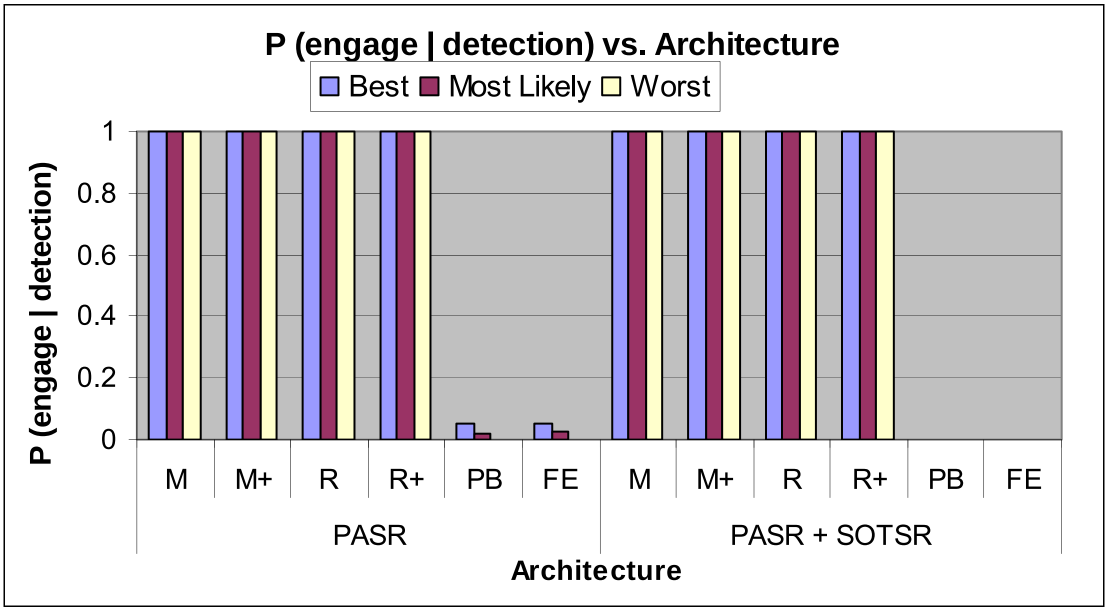

Figure 66. P (engage | detection) vs. Architecture

Figure 67 depicts the systems overall probability of detection, P(detect). Initially, it appears that both radars performed perfectly; however, when reviewing the preliminary model, it revealed that the shipboard radars rarely made a detection at all. In fact, it was the inorganic, space-based sensors that detected it every time. This will be a point of refinement for additional modeling. In order to get a breakout between radar systems for the probability of detection, the inorganic sensors were eliminated from the model. This left only the shipboard radars to detect a threat missile, and therefore differentiated them in terms of performance.

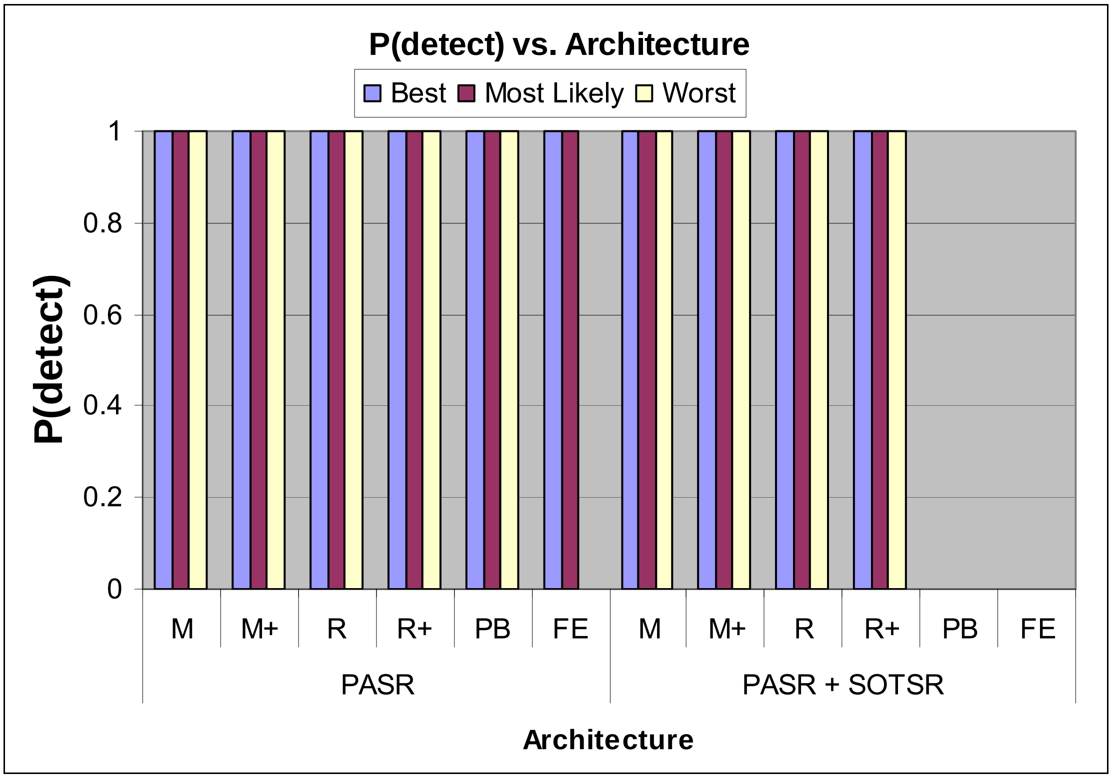

Figure 67. P(detect) vs. Architecture

The probability of kill, as depicted in Figure 68, was an initial input into the model, so this graph only confirms that the model is producing the correct results. The probability of kill for the missile interceptors and railgun interceptors were initialized at 0.8, the free electron DEW to 0.9, and the particle beam DEW to 0.95. These values are based on recommendations of technical experts and research.[75] These results are verified above in the probability of kill graph.

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[75] Gerald Brown, Matthew Carlyle, and Douglas Diehl, eds., “A Two Sided Optimization for Theater Ballistic Missile Defense,” Operations Research Department, Naval Postgraduate School, Monterey, CA, 2005, pp. 745-762.

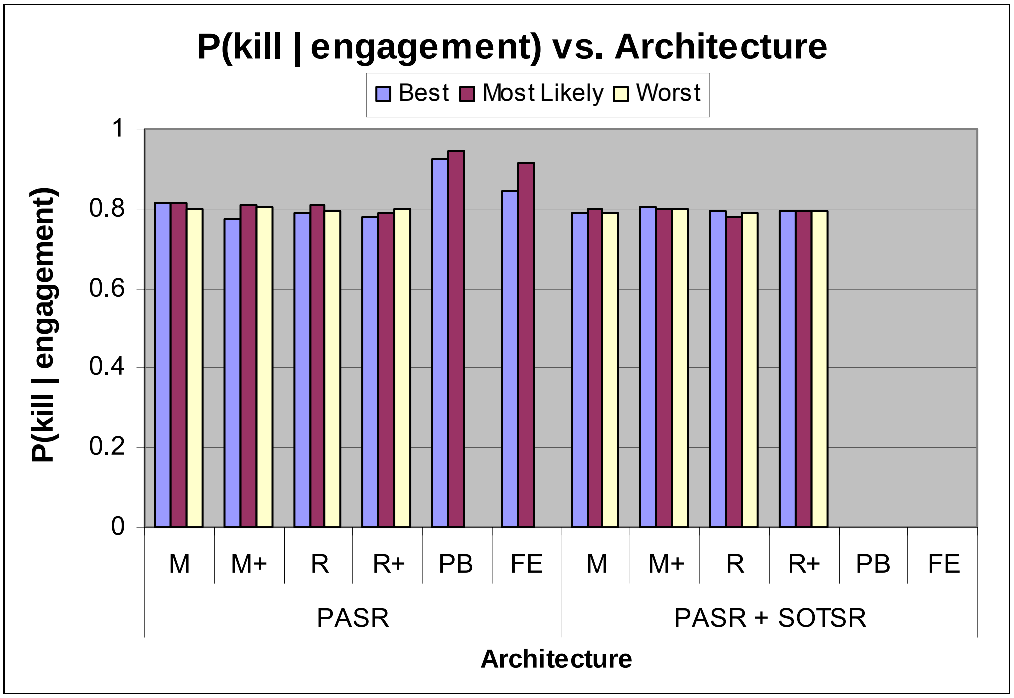


Figure 68. P(kill | engagement) vs. Architecture

Much like the evaluation of the probability of kill, probability of false alarm, as depicted in Figure 69, was also a fixed input to the model that remained constant through all scenarios and architectures. Though it is obvious that the weapon would not have an effect on probability of false alarm, it is not obvious that the radar would not have an effect on this parameter. It was determined from technical experts working with current phased array radars, that 0.02 was an acceptable level for false alarm. After speaking with Dr. David Jenn, the designer of the SOTSR, he predicted that the addition of the SOTSR would yield no significant impact on the overall false alarm rate of the radar sensor system.

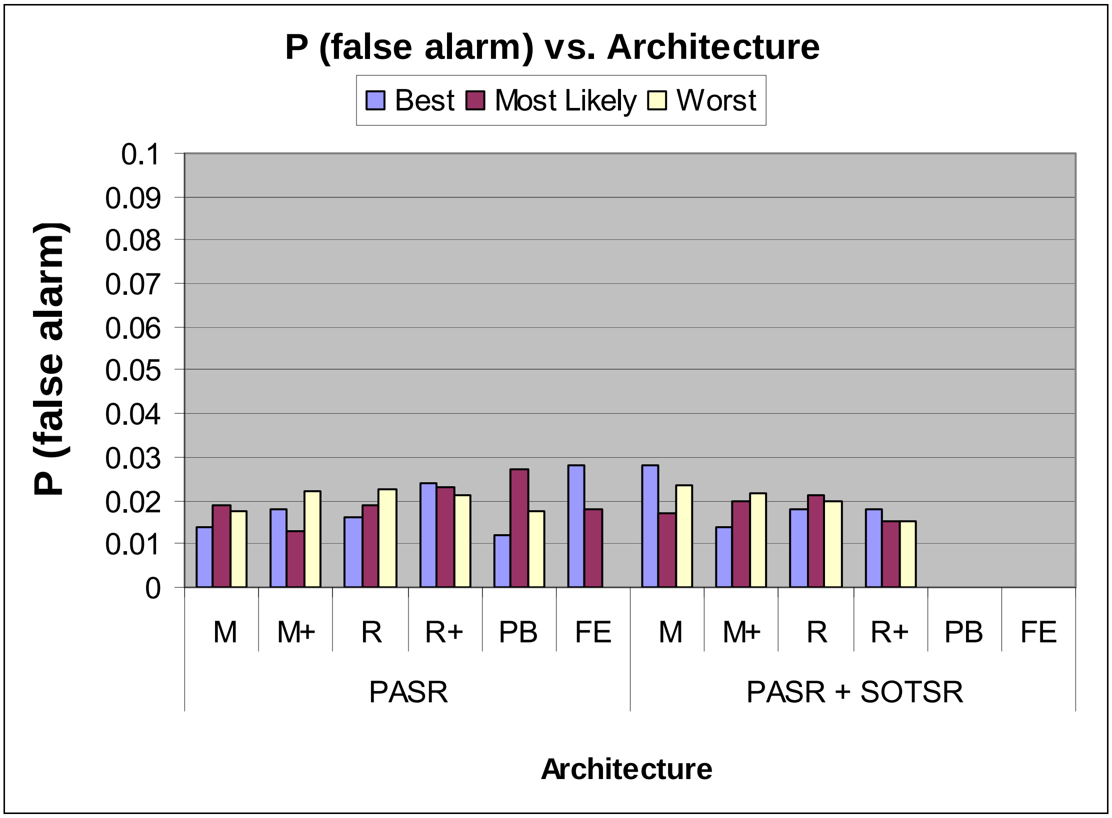


Figure 69. P (false alarm) vs. Architecture

The probability of handoff, as depicted in Figure 70, is a function of both weapon and radar capability. The radar, firstly, must be able to detect the threat missile. Without a detection, the weapon will not engage the target. However, extending the detection range with the SOTSR, does not affect the probability of handoff because even though a detection is made from a greater range, the detection range of the SOTSR is greater than the maximum engagement range of any of the intercepts. However, in the case of the DEWs, their lethal range was so short that the radar was able to detect and maintain a track on the threat missile, but rarely did the threat missile come within a close enough proximity for the free electron or particle beam weapons to engage it. This also led to the elimination of the DEW from further testing.

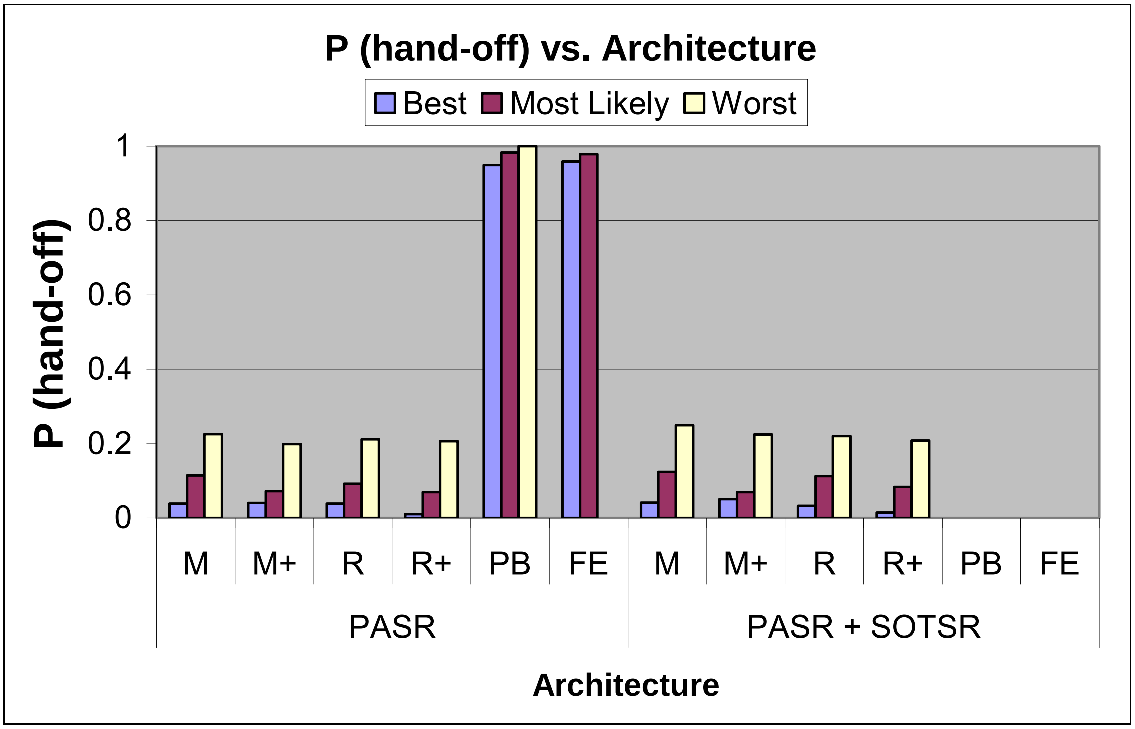


Figure 70. P (handoff) vs. Architecture

The detect through BDS metric, as depicted in Figure 71, measures the total time each architecture takes from the time of detection of a threat missile to process the data, determine a firing solution, engage the threat missile, and conduct BDA. The results show that as the velocity of the interceptor increases, the time to complete this cycle decreases, as to be expected. Among scenarios, as the severity of the scenario increased, the cycle time increased as well. This was due to the positioning of the various launch sites and target areas in addition to the fact that there are many more threat missiles launched with each increasing scenario. The DEW performed extremely well according to this metric. The weapon engages at the speed of light, so the engagement portion of the detect to engage cycle is virtually 0. However, due to its short lethal range, it remained an infeasible alternative for BMD.

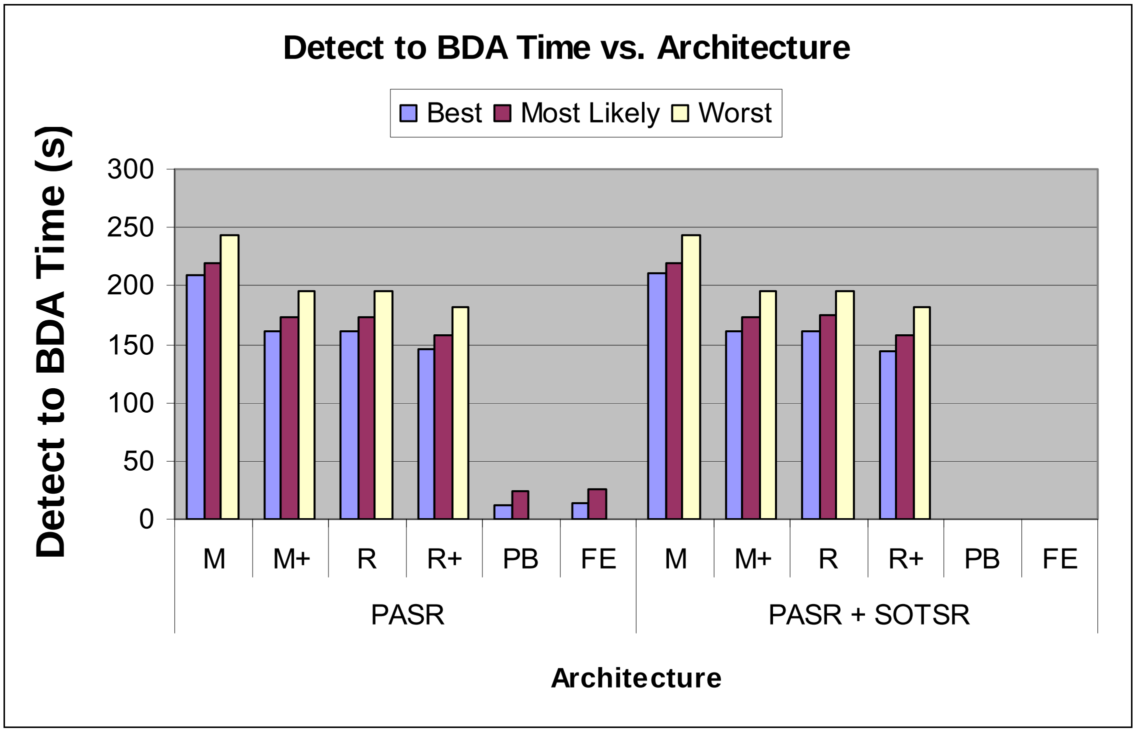


Figure 71. Detect to BDA Time vs. Architecture

This MOP, as shown in Figure 72, evaluates each architecture by the time left after a full cycle of detection through BDA until the end of threat missile midcourse. This gives insight to an architecture's ability to reengage the target or handoff to an asset with higher probability of destroying the threat missile. This metric yielded a few obvious trends among the various architectures.

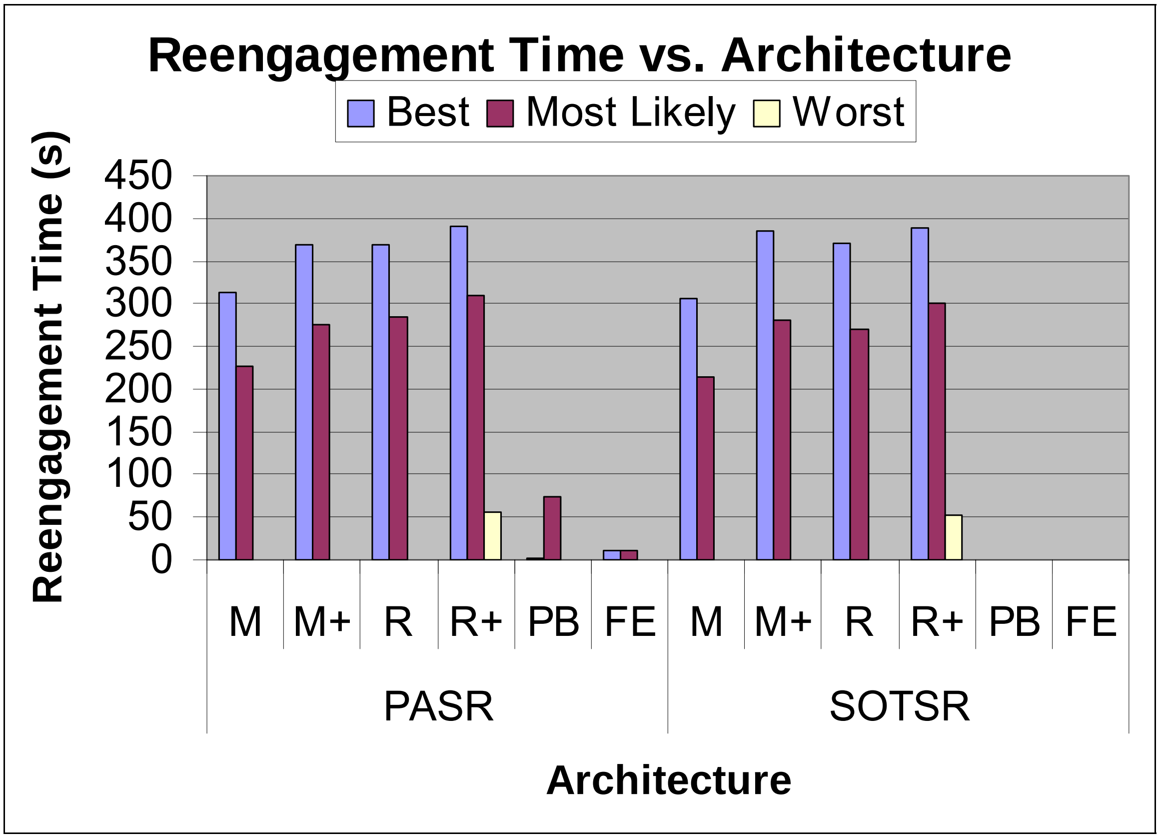


Figure 72. Reengagement Time vs. Architecture

First, as the weapon's speed and range increase, the time left to reengage also increases. This is to be expected since it will take less time for the interceptor to engage the target. This, however, was not the case with the directed energy interceptors. This can be attributed to the interceptors' short lethal engagement range. Though the DEWs engage at the speed of light, the threat missile rarely comes within their lethal range, and once it finally does, the threat missile is near the end of midcourse.

Secondly, as the scenario becomes more stressing, the time left to reengage decreases. This is due to the fact that system performance is degraded with increasing stress to the scenario as a result of more missile tracks and less than optimal environmental conditions. In fact, as shown in the worst scenario, only the faster railgun round had any time to reengage the threat missile.

Third, with the greater detection range the SOTSR provides, it seems feasible that the architectures including the SOTSR would have greater reengagement times; however, as evident from the above graph, they do not. This leads to a point of refinement for retesting in order to generate a breakout between the radars' performance. This was accomplished by reevaluating the technical parameters and inputs for the SOTSR with Dr. Jenn.

Although many of the results from the first iteration of modeling and analysis proved to be inconclusive and did not produce a breakout between competing architectures, there was a tremendous amount of value that came from it as well. As a result of the poor performance of the DEWs, 4 of the initial 12 architectures were eliminated. This allowed for more focus to be brought to the remaining architectures during the second iteration. Secondly, it made points of refinement evident in order to get a breakout between the weapon and radar options. Lastly, the results verified where the model was working correctly and also where changes needed to be made.

Upon refinement, the model allowed the remaining competing architectures to be evaluated against each other using the metrics derived in Figure 65. The refinement included more accurate detection ranges, the removal of inorganic detection sensors, performance characteristics in degraded states for the competing radar systems, and terminal guidance consideration for the remaining interceptor alternatives.

5.7 REFINED DATA

5.7.1 Refined System Model

The preliminary system models were refined after the initial tests due to their shortcomings and failure to produce a preferred system architecture. One of the major changes to the model was to the nonorganic inputs. The satellite probability of detection was made 0, essentially eliminating the satellites. Without satellites the ship would be operating independently, so the radar calculations in Extend needed to be improved. For the phased array radar, a block was added to calculate detection height based on the radar range equation. The SOTSR model was improved by adding separate range calculations for the SOTSR and cued phased array radar, as well as separate delays for detection. The other change that occurred was with the interceptor inputs. Rather than trying to input a likely probability of kill for a single shot, an overall probability of kill for a salvo was used. The same scenarios were used for the refined system model. The refined system model was successful in producing a preferred architecture and more closely reflected reality than the preliminary system model. Figure 72-1 shows an overview of the refined system model. Outputs remained exactly the same as the preliminary model. The only change to the environmental factors was the elimination of the best case scenario. The decision variables changed to reflect the elimination of the DEW as a possible architecture.

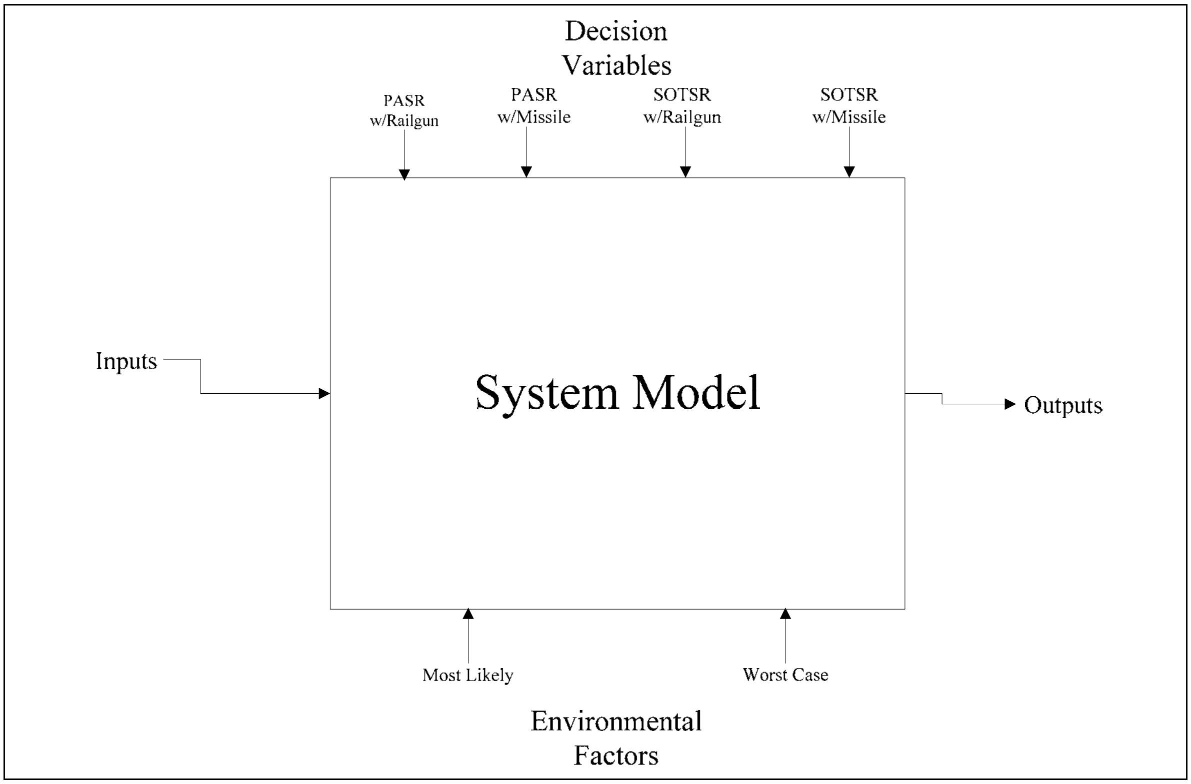


Figure 72-1. Refined System Model

5.7.1.1 Inputs

A major change to the results of the refined model came from changing various inputs. The inputs needed to be changed in order to determine a preferred architecture. In the previous round of simulation, the satellites detected every missile before the ship could, so no preferred radar was determined. For this round of simulations, the satellites were essentially eliminated by making their probability of detection equal to 0. Detection ranges were also changed to reflect the new radar calculations. The SOTSR ranges were estimated using AREPS. Multifunctional phased array ranges were calculated based on the current SPY-1B system. The cued phased array range was increased to reflect the range increase from focusing the radar energy in a given direction. Together, the change in inputs allowed a preferred radar to be chosen. For the refined model, only the most likely and worst case scenarios were used.

5.7.1.1.1 Nonorganic Characteristics. The nonorganic characteristics, which focused on the satellite capabilities, were changed to eliminate the satellites. The inputs were still necessary as the satellites were left in the model. The biggest change was making the satellites' probability of a missed detection 1, so they would never detect the missile. Table 20 shows the nonorganic inputs to the refined system model.

	Best Case		**Most Likely**		**Worst Case**	
Model Inputs	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
P(Sat Missed Det)	Not Used for Refined Model		1	n=1	1	n=1
Sat Sweep Rate			8	1	10	2
Detection Delay for Satellite			3	0.5	10	2
Max. Target Detected at a time, Sat Only			100		100	
Processing Delay for Sat			1	0.5	3	1
Max. Processed at a time (Sat Only)			1,000		1,,000	
Comms Delay for Sat			1	0.02	2	0.1
Max. detection simultaneously communicated by Sat Only			1,000		1000	

Table 20. Refined System Model Nonorganic Asset Inputs

5.7.1.1.2 Organic Characteristics. Most organic characteristics were left the same for the refined round of simulation. Changes were made to the detection ranges for the multifunctional phased array radar to reflect the difference in range between cued and noncued phased array radar. The SOTSR range was changed based on inputting the conformable radar characteristics into AREPS. Tables 21 and 22 show the PASR and SOTSR inputs to the refined system model, respectively.

	Best Case		**Most Likely**		**Worst Case**	
Model Inputs	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Ship Detection Range (km)	Not Used for Model Refinement		730		730	
P(Sensor System Detection)			0.9	n=1	0.85	n=1
Sweep Rate for System			12	6	15	6
P(False Alarm)			0.02	n=1	0.02	n=1
Detection Delay for Ship			4	1	8	2
Max. targets simultaneously detected			1,000		1,000	
Processing Delay for system			1	0.2	2	0.5
Max. targets processed at a time			1,000		1,000	
Tracking Stage			**Mean**	**SD**	**Mean**	**SD**
P(keeping track)			0.9	n=1	0.9	n=1
Time to reacquire track			6	2	7	2
Tracking Delay			2	0.5	3	0.7
Max. Simultaneous Tracks			1,000		1,000	
Track Processing Delay			1	0.5	2	0.5
Max. Simultaneous Tracks Processed			1,000		1,000	
Communicate Tracks Delay			1	0.5	2	0.5
Max. Tracks Communicated at Once			1,000		1,000	
Identification Inputs			**Mean**	**SD**	**Mean**	**SD**
Identification Delay			4	0.5	6	1
Max. Targets Simultaneously Identified			1,000		1,000	
Threat Evaluation Inputs			**Mean**	**SD**	**Mean**	**SD**
Priority 1% to Mid Course			20			
Priority 2% to Mid Course			40			
Priority 3% to Mid Course			60			
Priority 4 % to Mid Course			80			
Threat Evaluation Delay			6	1	7	1.5
Weapons Pairing Inputs			**Mean**	**SD**	**Mean**	**SD**
Delay for Weapons Pairing			2.5	0.4	3.5	0.6
Max. Targets Paired at a Time			1		1	
BDA Stage			**Mean**	**SD**	**Mean**	**SD**
Time to Conduct BDA			0.5	0.01	0.5	0.01
Max. Simultaneous BDAs			1,000		1,000	
Prob. Good BDA			0.9	n=1	0.9	n=1

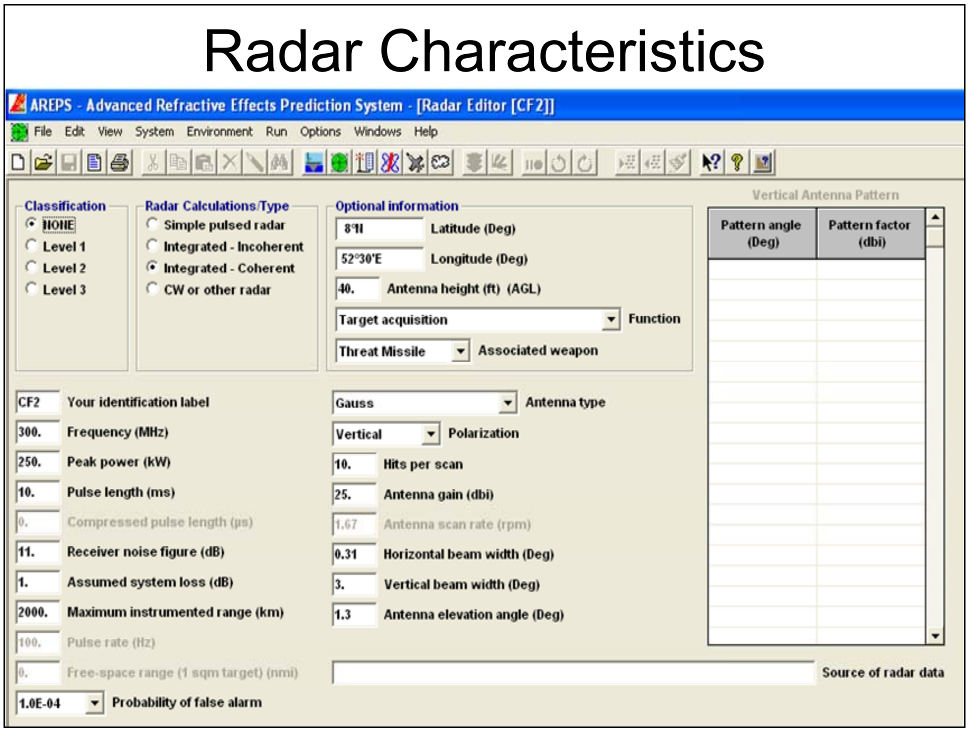
Table 21. Refined System Model PASR Inputs

	Best Case		Most Likely		Worst Case	
Model Inputs	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
SOTSR Range	Not Used for Model Refinement		1,500		1,500	
P(SOTSR Missed Detection)			0.1	n=1	0.15	n=1
SOTSR Detection Delay			10	2	15	3
PASR Cued Range (km)			970		970	
P(Sensor System Detection)			0.95	n=1	0.9	n=1
Sweep Rate for System			12	6	15	6
P(False Alarm)			0.02	n=1	0.02	n=1
Detection Delay for Ship			4	1	6	1
Max. targets simultaneously detected			1,000		1,000	
Processing Delay for system			1	0.2	2	0.5
Max. targets processed at a time			1,000		1,000	
Tracking Stage			**Mean**	**SD**	**Mean**	**SD**
P(keeping track)			0.9	n=1	0.9	n=1
Time to reacquire track			6	2	7	2
Tracking Delay			2	0.5	3	0.7
Max. Simultaneous Tracks			1,000		1,000	
Track Processing Delay			1	0.5	2	0.5
Max. Simultaneous Tracks Processed			1,000		1,000	
Communicate Tracks Delay			1	0.5	2	0.5
Max. Tracks Communicated at Once			1,000		1,000	
Identification Inputs			**Mean**	**SD**	**Mean**	**SD**
Identification Delay			4	0.5	6	1
Max. Targets Simultaneously Identified			1,000		1,000	
Threat Evaluation Inputs			**Mean**	**SD**	**Mean**	**SD**
Priority 1% to Mid Course			20			
Priority 2% to Mid Course			40			
Priority 3% to Mid Course			60			
Priority 4% to Mid Course			80			
Threat Evaluation Delay			6	1	7	1.5
Weapons Pairing Inputs			**Mean**	**SD**	**Mean**	**SD**
Delay for Weapons Pairing			2.5	0.4	3.5	0.6
Max. Targets Paired at a Time			1		1	
BDA Stage			**Mean**	**SD**	**Mean**	**SD**
Time to Conduct BDA			0.5	0.01	0.5	0.01
Max. Simultaneous BDAs			1,000		1,000	
Probability Good BDA			0.9	n=1	0.9	n=1

Table 22. Refined System Model SOTSR Inputs

The conformable SOTSR was validated using the Advanced Refractive Effects Prediction System (AREPS). The AREPS program was provided by the Space and Naval Warfare Systems Command (SPAWAR). The program is commonly used by the U.S. Navy to predict the performance of radars. Radar characteristics are entered into the program, along with geographic location, weather, target characteristics, and the host platform.

Using data provided by TDSI students a conceptual radar was modeled in the AREPS program, Figure 73. The radar was titled Conformable version 2 (CF2). A notional threat missile was entered into the system, Figure 74. It was necessary to input a threat missile in order to test the system performance. The ship platform inputs were limited to location and height of radar. Ship inputs are shown in Figure 75.



Radar Characteristics

Classification
- ● NONE
- ○ Level 1
- ○ Level 2
- ○ Level 3

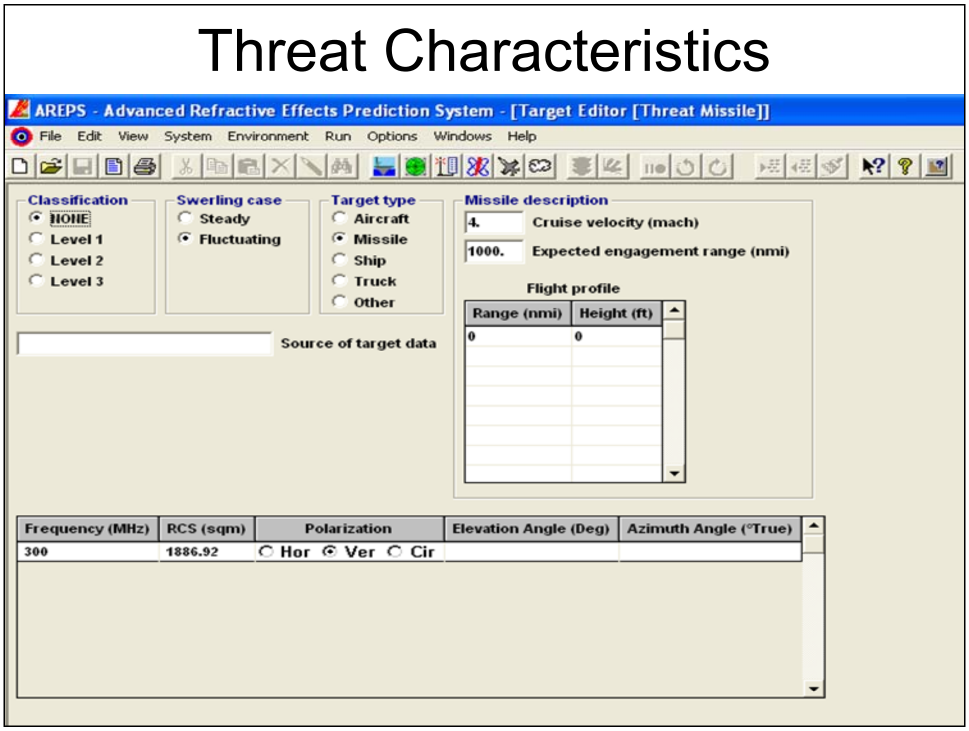
Radar Calculations/Type
- ○ Simple pulsed radar
- ○ Integrated - Incoherent
- ● Integrated - Coherent
- ○ CW or other radar

Optional information
- 8°N Latitude (Deg)
- 52°30'E Longitude (Deg)
- 40. Antenna height (ft) (AGL)
- Target acquisition Function
- Threat Missile Associated weapon

- CF2 Your identification label
- 300. Frequency (MHz)
- 250. Peak power (kW)
- 10. Pulse length (ms)
- 0. Compressed pulse length (µs)
- 11. Receiver noise figure (dB)
- 1. Assumed system loss (dB)
- 2000. Maximum instrumented range (km)
- 100. Pulse rate (Hz)
- 0. Free-space range (1 sqm target) (nmi)
- 1.0E-04 Probability of false alarm

- Gauss Antenna type
- Vertical Polarization
- 10. Hits per scan
- 25. Antenna gain (dbi)
- 1.67 Antenna scan rate (rpm)
- 0.31 Horizontal beam width (Deg)
- 3. Vertical beam width (Deg)
- 1.3 Antenna elevation angle (Deg)
- Source of radar data

Figure 73. AREPS Radar Editor Screenshot



Threat Characteristics

AREPS - Advanced Refractive Effects Prediction System - [Target Editor [Threat Missile]]

Classification
● NONE
○ Level 1
○ Level 2
○ Level 3

Swerling case
○ Steady
● Fluctuating

Target type
○ Aircraft
● Missile
○ Ship
○ Truck
○ Other

Missile description
4. Cruise velocity (mach)
1000. Expected engagement range (nmi)

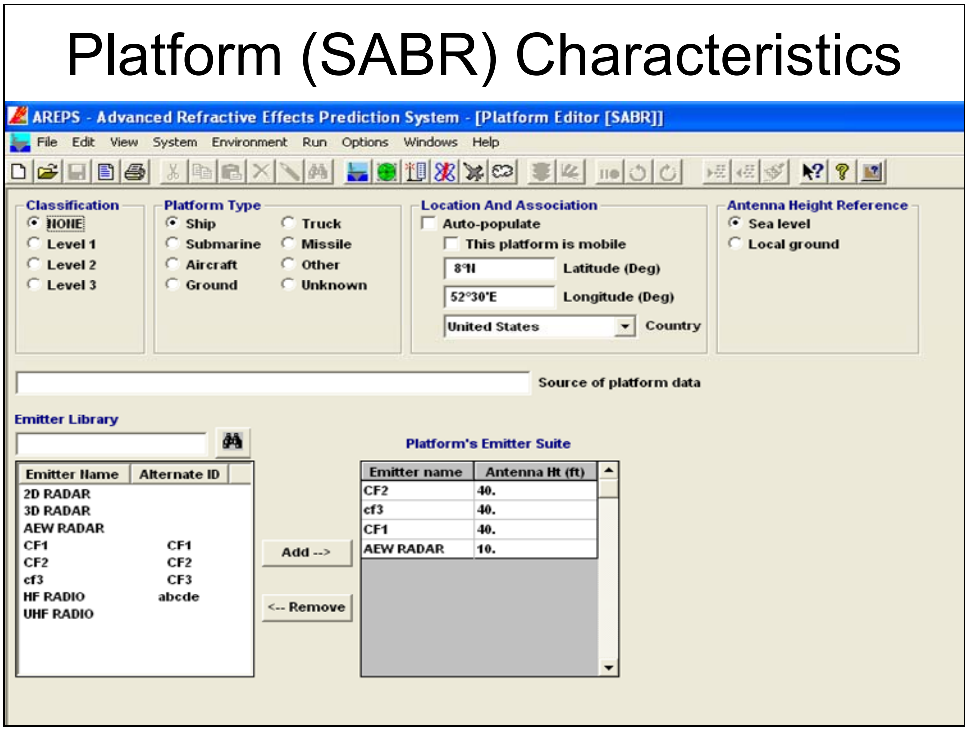
Flight profile

Range (nmi)	Height (ft)
0	0

Source of target data

Frequency (MHz)	RCS (sqm)	Polarization	Elevation Angle (Deg)	Azimuth Angle (°True)
300	1886.92	○ Hor ● Ver ○ Cir		

Figure 74. AREPS Threat Editor Screenshot



Platform (SABR) Characteristics

AREPS - Advanced Refractive Effects Prediction System - [Platform Editor [SABR]]

Classification
● NONE
○ Level 1
○ Level 2
○ Level 3

Platform Type
● Ship
○ Submarine
○ Aircraft
○ Ground
○ Truck
○ Missile
○ Other
○ Unknown

Location And Association
☐ Auto-populate
☐ This platform is mobile
8°N Latitude (Deg)
52°30'E Longitude (Deg)
United States Country

Antenna Height Reference
● Sea level
○ Local ground

Source of platform data

Emitter Library

Emitter Name	Alternate ID
2D RADAR	
3D RADAR	
AEW RADAR	
CF1	CF1
CF2	CF2
cf3	CF3
HF RADIO	abcde
UHF RADIO	

Platform's Emitter Suite

Emitter name	Antenna Ht (ft)
CF2	40.
cf3	40.
CF1	40.
AEW RADAR	10.

Figure 75. AREPS Platform Editor Screenshot

The output of the system can be seen in Figure 76, which shows what was predicted. A line of sight detection area is shown by the area in red. The area in red is a probability of detection greater than 0.80. By running the cursor over the red region it the probability of detection is mostly greater than 0.99. This validates the calculated predictions.

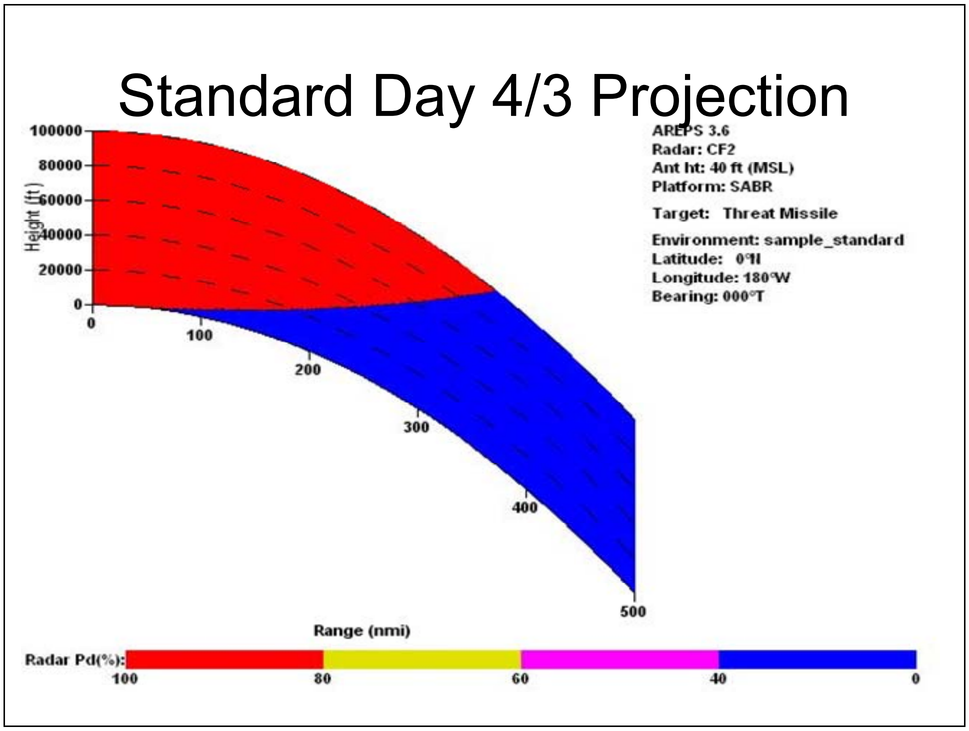


Figure 76. AREPS Probability of Detection of SABR System

5.7.1.1.2 Interceptor Inputs. The interceptor inputs used for the refined system model are shown in Table 23.

			Most Likely	Stressed	Best Case		Most Likely		Stressed	
Interceptor Type	**Speed**	**Time Correction Factor**	**Required P(k)**	**Required P(k)**	**Max Range**	**Max Height**	**Max Range (km)**	**Max Height (km)**	**Max Range (km)**	**Max Height (km)**
Missile	6 km/s	Multiply by 1 sec	0.95	0.95	Not Used for Refined Model		1,800	750	1,800	750
Missile	8 km/s	Multiply by 1 sec	0.95	0.95			2,400	1,000	2,400	1,000
Railgun	8 km/s	Multiply by 1 sec	0.95	0.95			2,200	1,000	2,200	1,000
Railgun	10 km/s	Multiply by 1.12 secs	0.95	0.95			4,400	2,000	4,400	2,000

Table 23. Refined System Model Interceptor Inputs

To calculate the overall probability of kill, it was assumed that all shots are statistically independent of each other. Therefore, the probability of kill for a given salvo, assuming every shot has an equal probability of kill, can be calculated using the equation $P(k) = 1 - (1 - Pssk)^n$, where n = the number of shots per salvo.[76] Tables 24 and 25 show a table of theoretical probabilities of single shot kill and the number of

---

[76] Daniel H. Wagner, W. Charles Mylander, and Thomas J. Sanders, *Naval Operations Analysis*, 3rd Ed., Naval Institute Press, Annapolis, MD, 1999, pp. 133-134.

rounds in a single salvo to achieve the desired probability of kill for a missile and railgun system, respectively.

	Most Likely	**Stressed**
Missile Pssk	**# of Missiles Required to Achieve > 0.95 Probability of Kill**	**# of Missiles Required to Achieve > 0.95 Probability of Kill**
0.7	3	3
0.8	2	2
0.9	2	2

Table 24. Refined System Model Table of Pssk vs. Missiles to Achieve P(k) > 0.95

	Most Likely	**Stressed**
Rail Gun Pssk	**# of Rounds Required**	**# of Rounds Required**
0.4	6	6
0.5	5	5
0.6	4	4

Table 25. Refined System Model Table of Pssk vs. Railgun Rounds to Acieve P(k) > 0.95

5.7.1.2 Refinements for Subcomponents

The system model was kept nearly the same for the second round of simulation. The only changes that occurred were in the inputs, as highlighted previously, and to the “Detection” hierarchical block. The PASR model was changed so it included a more accurate determination of whether a missile is detectable by a ship. The SOTSR model was modified to include separate time delays and range calculations for the conformal hull radar and the cued phased array radar.

5.7.1.2.1 PASR. The change to the phased array model included the addition of a “DE Equation” block to more accurately calculate the detection height of the radar and adding another determination of whether to hand off the missile. These changes improved the model by making the detection more realistic.

Detection Hierarchical Block Changes

The purpose of this section is to highlight the changes made to the “Detection” block. The changes are shown in Figure 77.

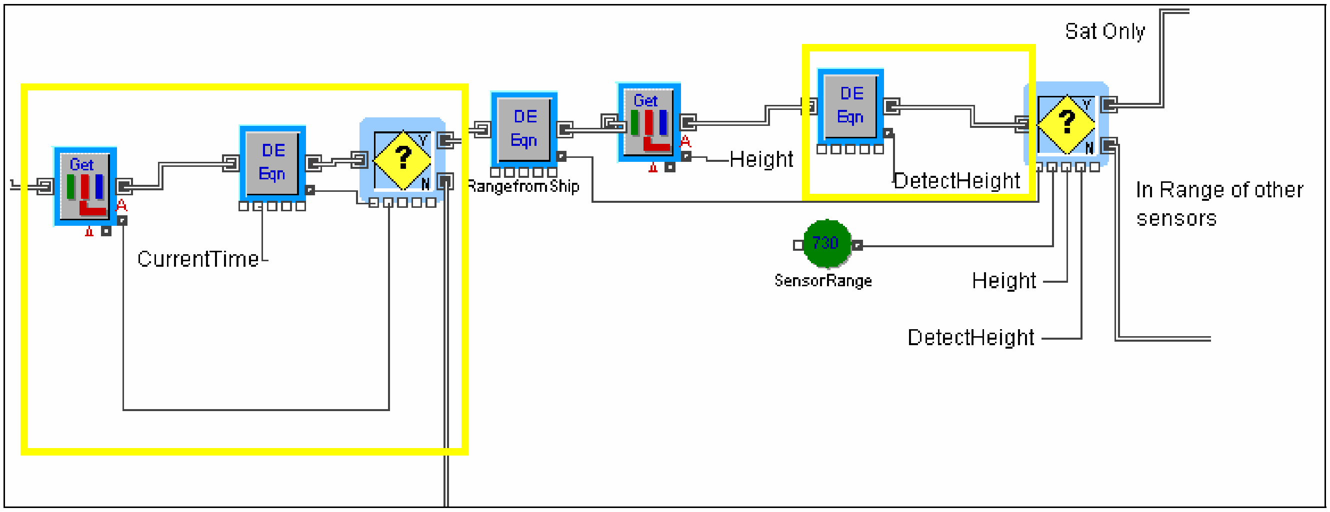
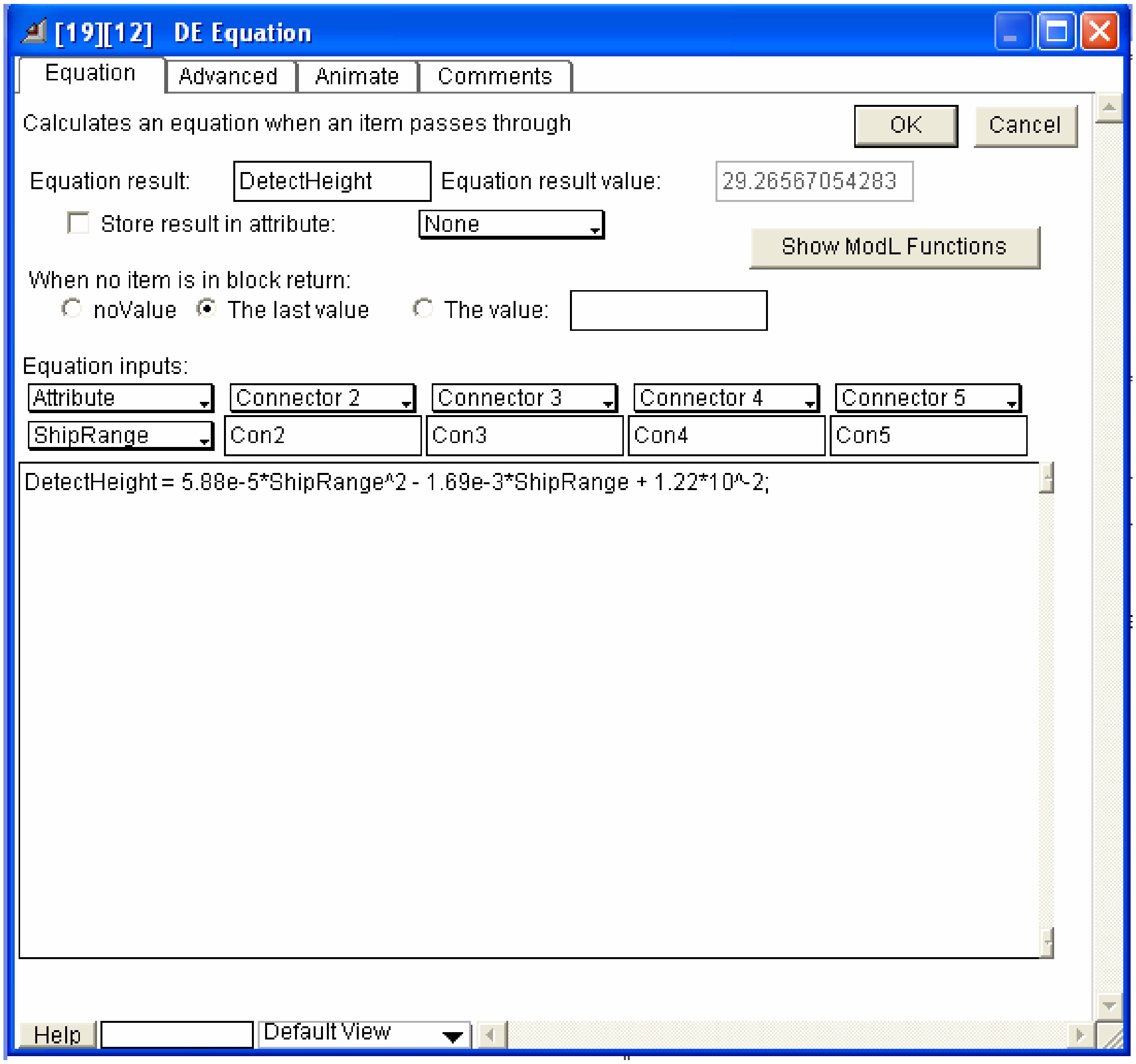


Figure 77. Refined System Model Changes to Detection Hierarchical Block

Figure 77 highlights the section of the Extend model that was modified during the refined phased of modeling. Changes are highlighted in yellow. The first change can be seen on the left side of Figure 77. This change added a determination of whether the missiles are still within the engagement window. In the preliminary model, this was not necessary because the satellites detected every missile well before it reached the end of midcourse. However, without the satellites in place, the missiles would get stuck in an infinite loop if they were never in range of the ship's radar. The highlighted "Decision" block passes items that have completed their midcourse phase to a "Combine" block, where they are combined with other leakers and exit the system. The other change to the model was the addition of the "DE Equation" block highlighted in yellow. The dialog for this block is shown in Figure 78. The block calculates the height at which the ship's radar can detect the missile at a given range. The equation is derived from the radar range equation $R_1 + R_2 = \sqrt{8/3 * R_{Earth} * h_1} + \sqrt{8/3 * R_{Earth} * h_2}$. This change made the actual time at which the missile was detected more accurate than the preliminary model because it was based on the range at a given time, rather than simply the maximum detection range.



Calculates an equation when an item passes through

Equation result: DetectHeight Equation result value: 29.26567054283

☐ Store result in attribute: None

When no item is in block return:
○ noValue ● The last value ○ The value:

Equation inputs:

Attribute	Connector 2	Connector 3	Connector 4	Connector 5
ShipRange	Con2	Con3	Con4	Con5

```
DetectHeight = 5.88e-5*ShipRange^2 - 1.69e-3*ShipRange + 1.22*10^-2;
```

Figure 78. Refined System Model Phased Array Radar Detection Height

5.7.1.2.2 SOTSR. It was necessary to change the skin of the ship radar models to more accurately reflect the behavior of the conformal radar. First, the conformal radar range is line of sight, so a "DE Equation" block needed to be added for this calculation. Also, the conformal radar cannot track the missile, so the ship's phased array radar must detect the missile after being cued by the conformal hull radar. Therefore, the same sequence of blocks as discussed for the phased array radar had to be added.

Detection Stage

The purpose of this section is to highlight the changes made to the "Detection" block for the skin-of-the-ship conformal radar combined with the phased array radar. Figure 79 shows the changes made to include the SOTSR in the refined system model.

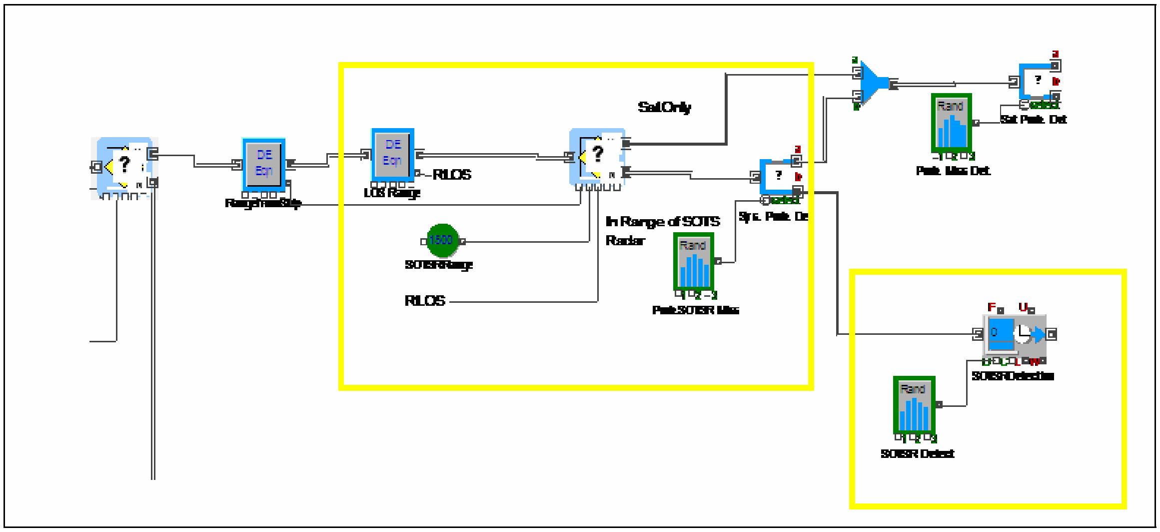
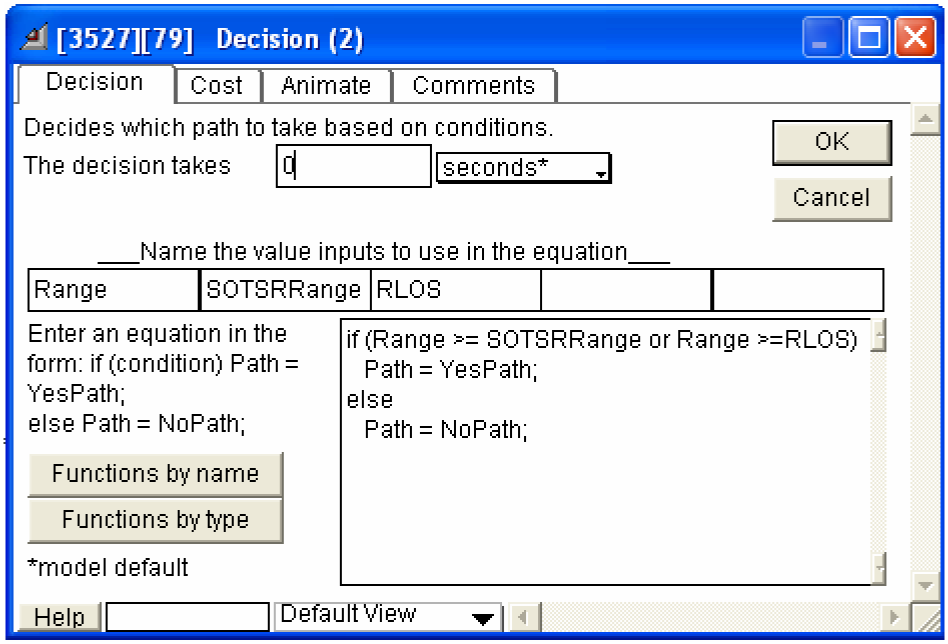


Figure 79. Refined System Model SOTSR Detection Block Addition of Conformal Radar

The changes made to the "Detection" block to account for the SOTSR are shown in Figure 79, highlighted in yellow. One change that was made that is not highlighted is the addition of a determination of whether the missile is still within the midcourse phase. The change for the conformal radar is the same as was discussed in PASR section. The "Decision (2)" block is seen on the left side of Figure 79. The first change to account for the conformal radar is the "DE Equation" block to calculate the radar line of sight range from the ship to the missile. This was done using the equation shown in Figure 80. This equation is normally written as $RLOS = \sqrt{17 * h_1} + \sqrt{17 * h_2}$, where h_1 and h_2 are both in meters. However, since the height of the missile, the variable "Zposition," is in kilometers, this height must be multiplied by 1,000 to convert to meters. h_1 is the height of the ship's radar. The next block in sequence is the "Decision (2)" block that receives the input from the "DE Equation" blocks for range from the ship to the missile and line of sight range, as well as a constant input of the radar's maximum detection range. The dialog for the "Decision (2)" block is shown in Figure 80.



Decides which path to take based on conditions.

The decision takes 0 seconds*

___Name the value inputs to use in the equation___

Range	SOTSRRange	RLOS		

Enter an equation in the form: if (condition) Path = YesPath; else Path = NoPath;

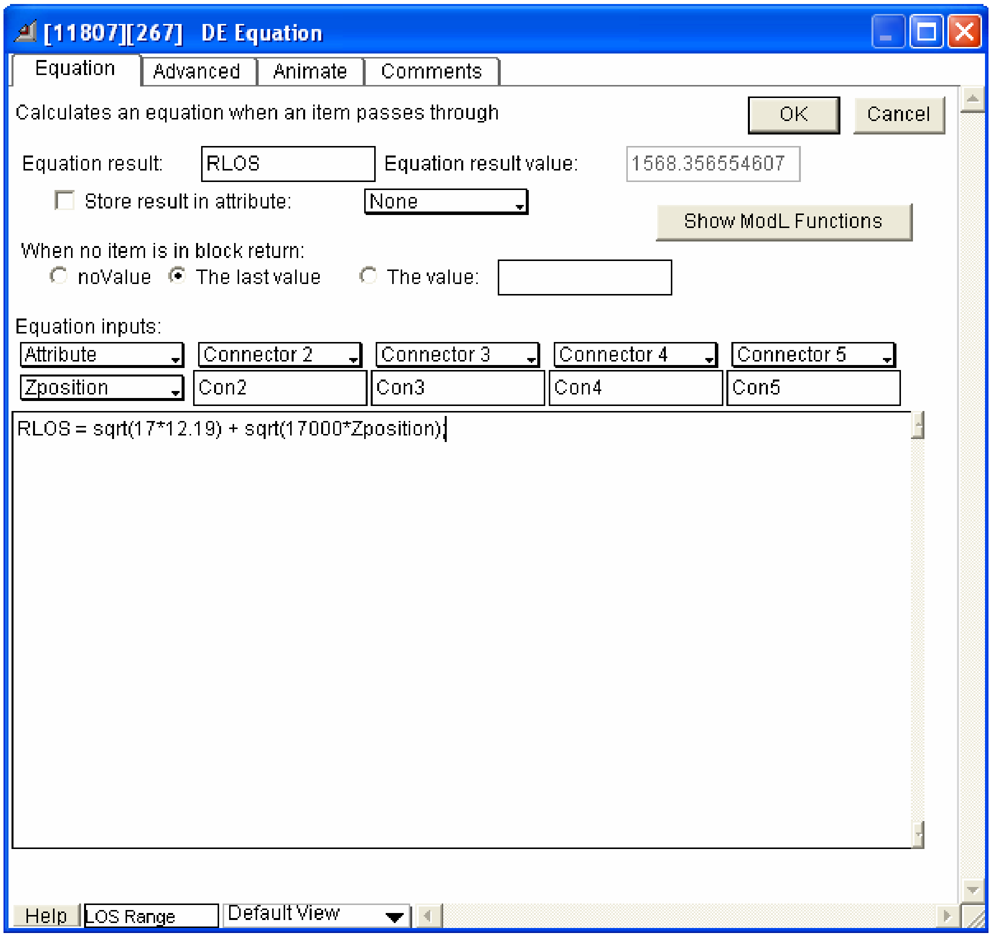
```
if (Range >= SOTSRRange or Range >=RLOS)
  Path = YesPath;
else
  Path = NoPath;
```

*model default

Figure 80. Refined System Model SOTSR within Range Decision

Items that are determined to be within range of the SOTSR exit the "Decision (2)" block through the "No" path. Items that are not yet within range exit through the "Yes" path where they are sent to the blocks simulating satellite detection.

After missiles are within range of the conformal radar, they enter a “Select DE Output” block that determines whether they are detected. Items that are not detected are passed to the satellites. Items that are determined to be detected enter an “Activity, Multiple” block as seen on the right side of Figure 80. This block accounts for the delay time that would occur for the conformal radar to detect a missile. After items exit the “Activity, Multiple” block, they are passed to the “Combine” block as seen on the left side of Figure 81.



Calculates an equation when an item passes through

Equation result: RLOS

Equation result value: 1568.356554607

☐ Store result in attribute: None

When no item is in block return:
○ noValue ● The last value ○ The value:

Equation inputs:

Attribute	Connector 2	Connector 3	Connector 4	Connector 5
Zposition	Con2	Con3	Con4	Con5

```
RLOS = sqrt(17*12.19) + sqrt(17000*Zposition);
```

Figure 81. Refined System Model SOTSR Radar Line of Sight Range

Items enter the “Combine” block seen on the left side of Figure 82 after being delayed for the conformal radar to detect them. These items then pass through the series of blocks that determine whether the missile is still within the engagement window. Missiles that still have completed their midcourse phase exit through the “No” path of the “Decision (2)” block and are considered leakers. Items that exit through the

"Yes" path are still within the engagement window and are sent to the "DE Equation" block seen on the right side of Figure 82 and left side of Figure 83.

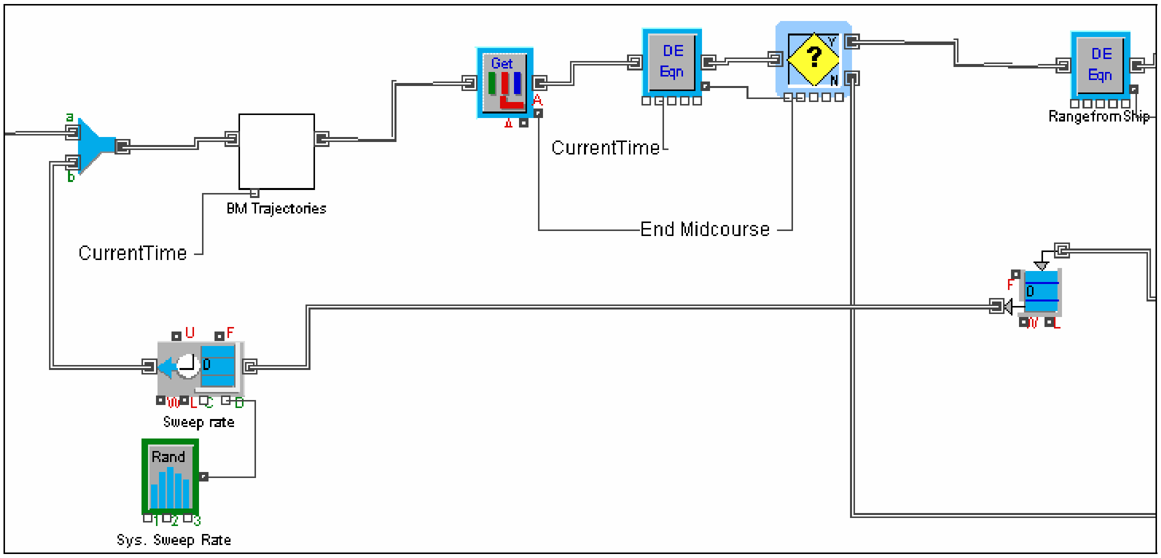


Figure 82. Refined System Model Phased Array Section Left Half

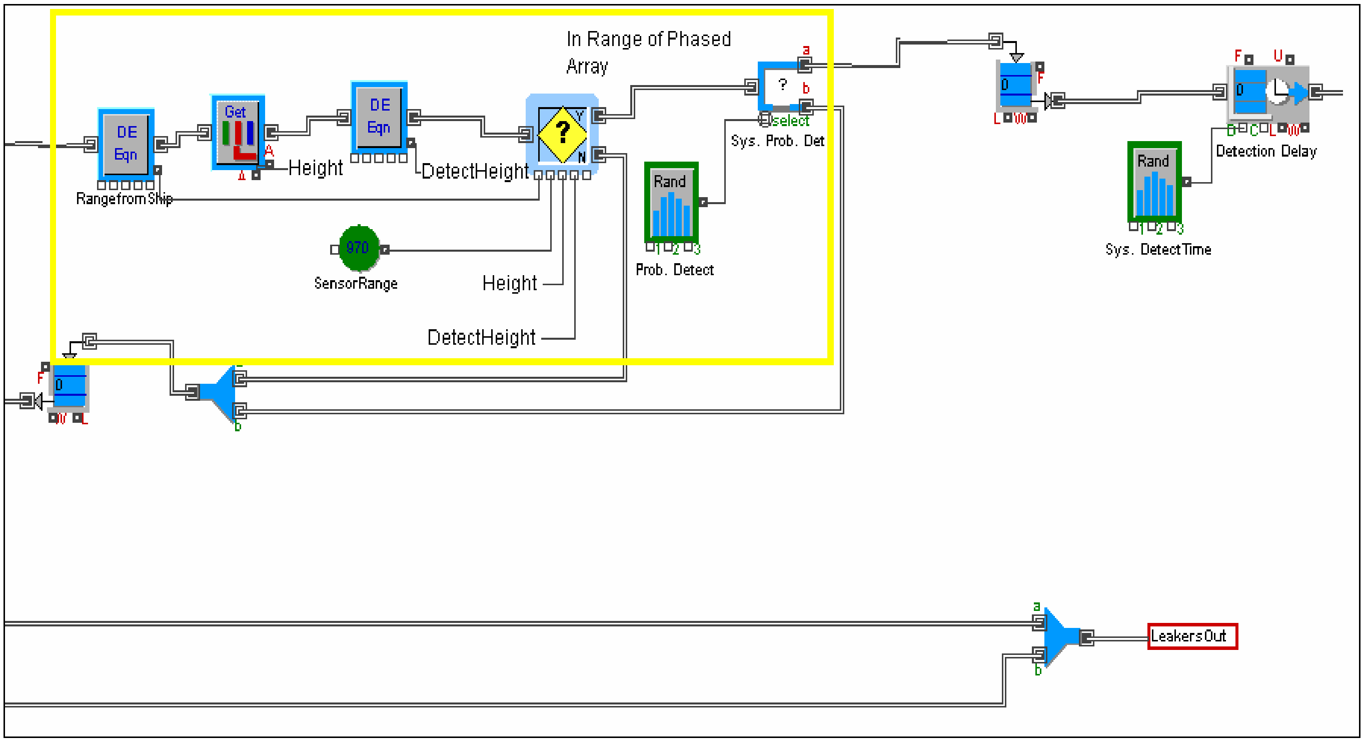


Figure 83. Refined System Model Phased Array Section Right Half

The bottom of Figure 83 shows where items that are considered leakers exit the "Detection" block. Items that are still within midcourse as determined by the "Decision (2)" block are passed to a "DE Equation" block. This block calculates the range from the missile to the ship. The blocks highlighted in yellow are used to determine when the missile is within range of the phased array radar. Items that are within range enter a “Select DE Output” block that routes items based on the probability of detection of the cued phased array radar. Items that are not detected go through a loop where they are delayed by the radar’s sweep rate before being recombined using the “Combine” block seen in Figure 82 with items that have passed through the “Activity, Multiple” block seen in Figure 79.

5.7.1.3 Improvements

The refinement phase of modeling improved the models in several ways. First, the determination of radar range was changed to more accurately reflect reality. Second, the conformal radar was combined with a phased array radar. Since the conformal radar cannot track targets, it cues the phased array radar on the same ship so it can focus on the direction of the detection. Therefore, it was necessary to add delays for both of these detections as well as determinations of when the missile is in range of both radars. The other major change during the refined phase of modeling came with the inputs. The satellites were essentially eliminated so the refined phase of modeling produced a preferred architecture.

5.7.2 Refined Data Analysis

A boxplot is a graphical representation of the data’s mean, median, and first and third quartile. The circled cross in each set is the representation of the data mean. The top line of the box represents the lower limit of the top quartile of the data, the middle line represents the median of the data, and the bottom line is the lower limit of the third quartile. In this data, the PASR radar system has a lower probability of detecting a BM, Figure 84.

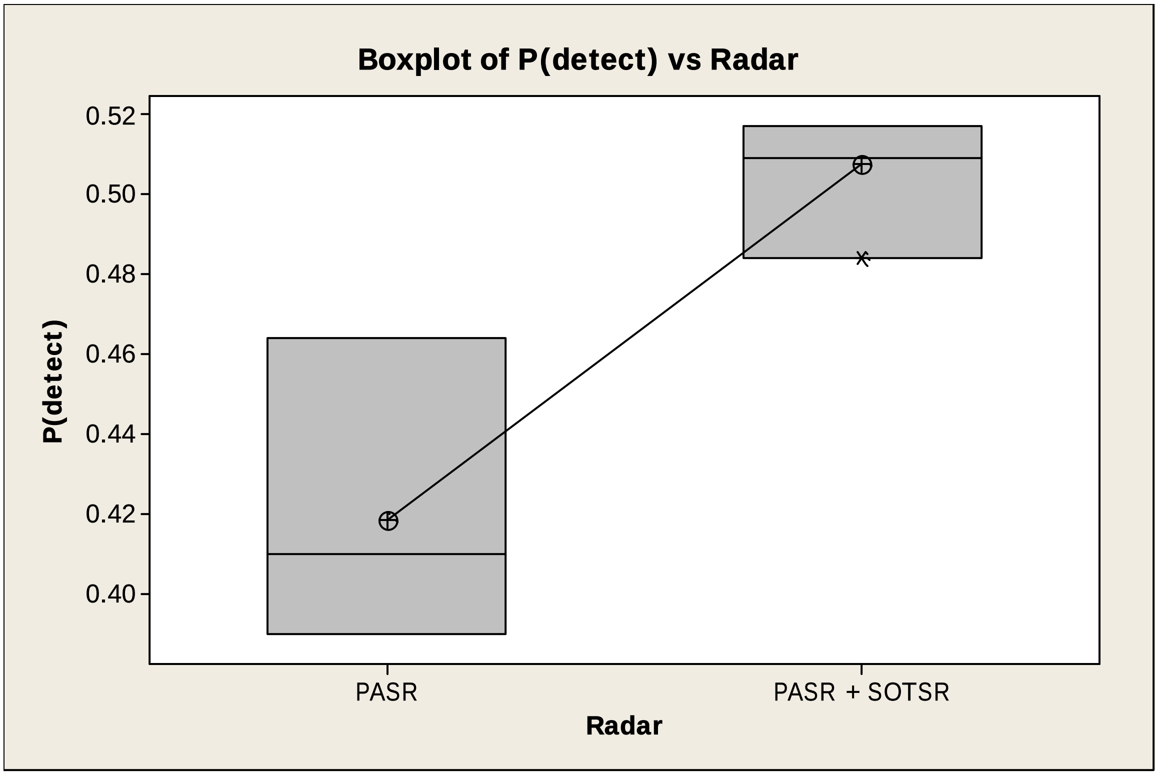
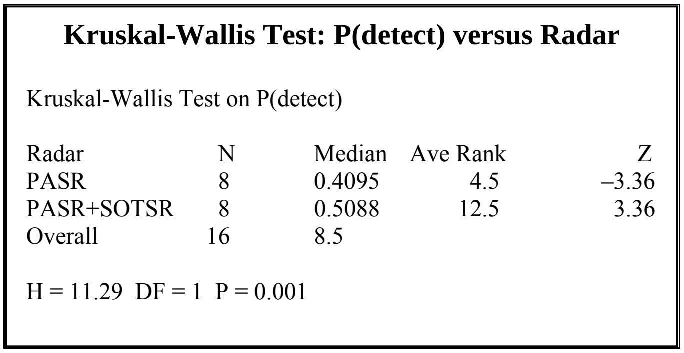


Figure 84. Boxplot of P(detect) vs. Radar

The Kruskal-Wallis analysis, Figure 85, compares the medians for each data set, and gives the statistical likelihood as to whether a statistically significant difference exists between systems. The P-value is used to determine whether the systems are the same. Since the P-value < alpha (which is the default 0.05 in this case) the null hypothesis of equal means is rejected, which supports the alternative hypothesis of unequal means. This indicates that the two systems have a statistically significant difference.



```
Kruskal-Wallis Test: P(detect) versus Radar

Kruskal-Wallis Test on P(detect)

Radar          N     Median  Ave Rank      Z
PASR           8     0.4095       4.5  –3.36
PASR+SOTSR     8     0.5088      12.5   3.36
Overall       16     8.5

H = 11.29  DF = 1  P = 0.001
```

Figure 85. Kruskal-Wallis Test: P(detect) vs. Radar

The one-way Analysis of Variance (ANOVA)[77] results, Figure 86, compare the means of each data set. There are two important aspects in this analysis, the ANOVA p-value and the Fisher Confidence Interval, which is a graphical representation of the difference between the systems, using a 95% confidence interval. For the ANOVA, since the P-value < alpha (which is the default 0.05 in this case) the null hypothesis of equal means is rejected, which supports the alternative hypothesis of unequal means. This indicates that the two systems have a statistically significant difference. For the Fisher CI, if the confidence interval includes zero, than it cannot be said with 95% confidence that there is a difference between the systems. In this data set, the interval does not include zero, so the conclusion is that with 95% confidence there is a difference between the systems.[78]

One-way ANOVA: P(detect) versus Radar

```
Source  DF        SS        MS      F      P
Radar    1  0.031922  0.031922  80.75  0.000
Error   14  0.005534  0.000395
Total   15  0.037456

S = 0.01988   R-Sq = 85.22%   R-Sq(adj) = 84.17%


                            Individual 95% CIs For Mean Based on
                            Pooled StDev
Level      N     Mean    StDev  ------+---------+---------+---------+---
PASR       8  0.41808  0.02605  (----*----)
SOTSR+PASR 8  0.50742  0.01058                              (----*----)
                            ------+---------+---------+---------+---
                                0.420     0.450     0.480     0.510

Pooled StDev = 0.01988


Fisher 95% Individual Confidence Intervals
All Pairwise Comparisons among Levels of Radar

Simultaneous confidence level = 95.00%


Radar = PASR subtracted from:

Radar          Lower  Center    Upper  ------+---------+---------+---------+-
--
SOTSR+PASR  0.06801  0.08933  0.11065                          (------*-----
)
                                       ------+---------+---------+---------+-
--
                                            0.000     0.035     0.070
0.105
```

Figure 86. One-Way ANOVA: P(detect) vs. Radar

---

[77] MINITAB, 14th Ed., "Analysis of Variance," Help-to-Go Files, http://www.minitab.com/support/docs/re114/helpfiles/statistics/AnalysisOfVariance.pdf

[78] Ibid.

Figure 87 represents the probability of handoff by the system, looking at each combination of weapon and radar. A lower P(handoff) is desirable, because handoff implies that the system failed. The graphical representation is the same as in the previous boxplot. By this metric, the SOTSR radar system is typically better than the PASR system. Within each radar system, the railgun outperforms the missile and, in both cases, the faster interceptor provides more desirable results.

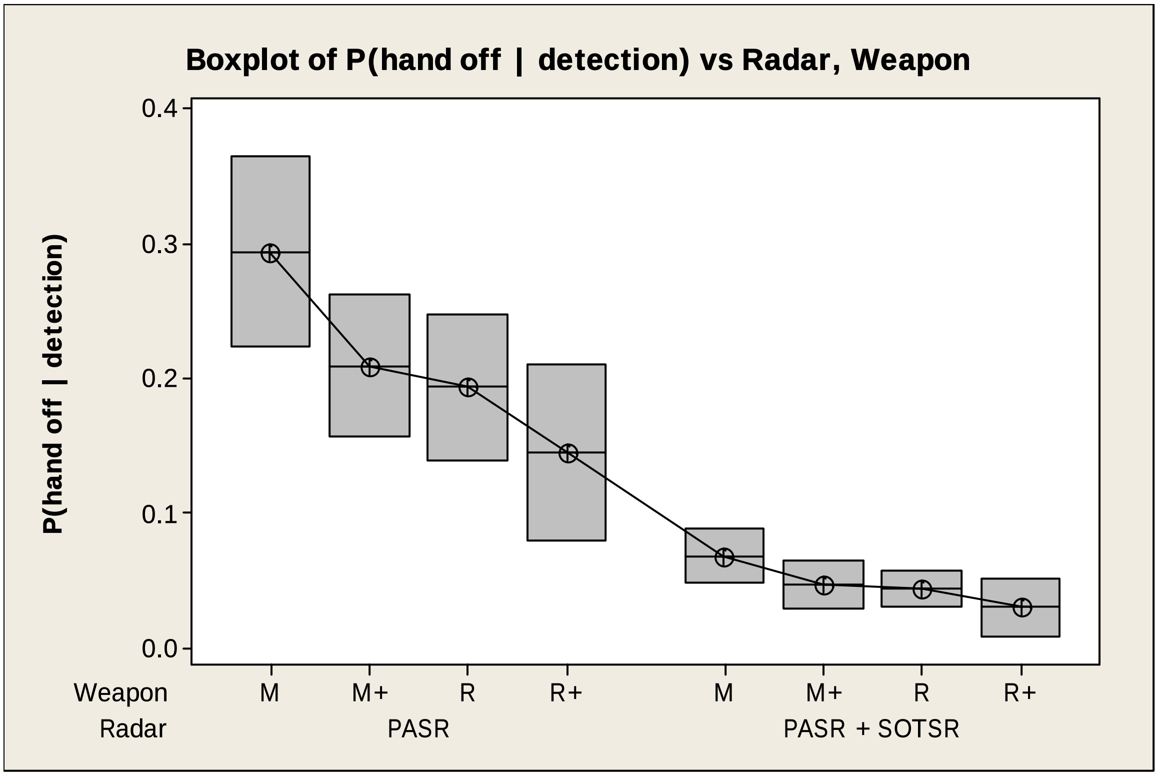


Figure 87. Boxplot of P(handoff | detection) vs. Radar, Weapon

Figure 88 represents the probability of engagement based solely on radar system. The SOTSR system is clearly the top performer in this metric, as it has 100% P(engage), due to having an increased detection range, with no variability in the data.

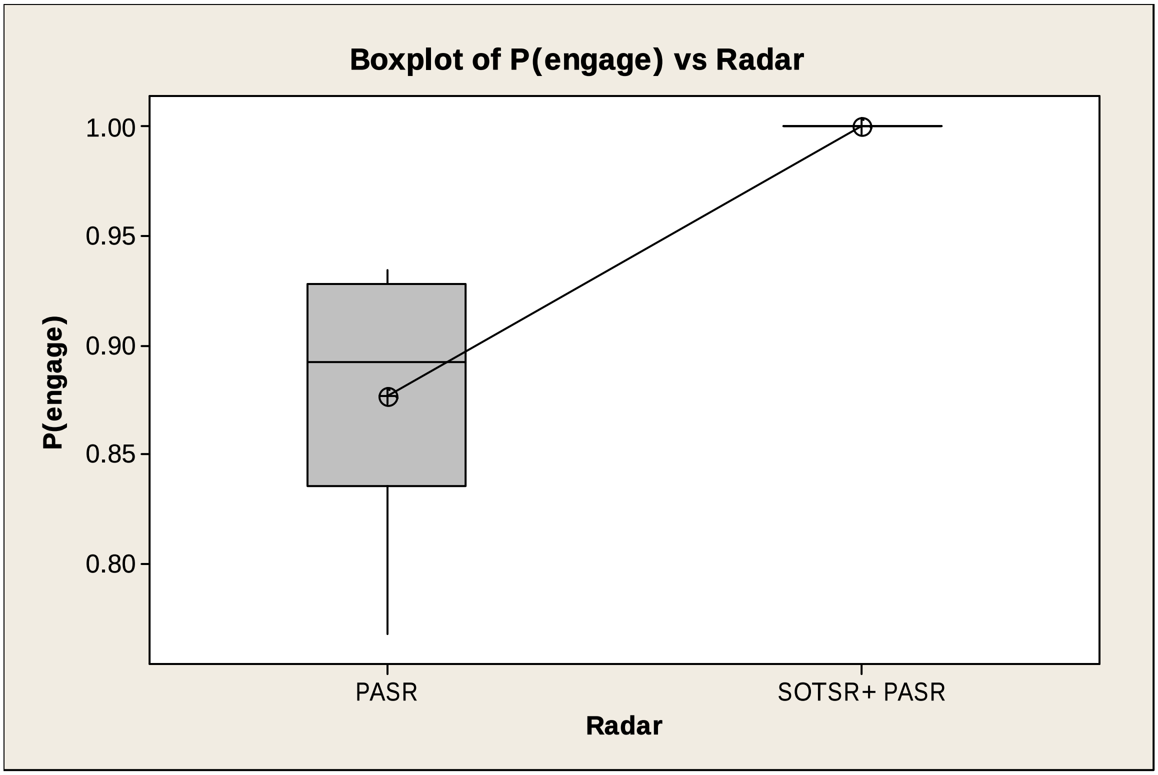


Figure 88. Boxplot of P(engage) vs. Radar

The Kruskal-Wallis analysis, Figure 89, of the medians of P(engage) for each radar system, shows a statistically significant difference between the P(engage) for the radars. From the respective boxplot, it is the SOTSR+PASR system which is the better performer, with a median of 1.00.

Kruskal-Wallis Test: P(engage) versus Radar

```
Kruskal-Wallis Test on P(engage)

Radar           N  Median  Ave Rank      Z
PASR            8  0.8921       4.5  -3.36
SOTSR+PASR      8  1.0000      12.5   3.36
Overall        16               8.5

H = 11.29  DF = 1  P = 0.001
```

Figure 89. Kruskal-Wallis Test: P(engage) vs. Radar

The one-way ANOVA of P(engage) for the radar system shows, Figure 90, with 95% confidence, that the two systems are not the same. The P(engage) of the SOTSR+PASR shows it to be the better system.

One-way ANOVA: P(engage) versus Radar

```
Source  DF       SS       MS      F      P
Radar    1  0.06083  0.06083  36.00  0.000
Error   14  0.02366  0.00169
Total   15  0.08448

S = 0.04111   R-Sq = 72.00%   R-Sq(adj) = 70.00%


                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level       N    Mean   StDev   -+---------+---------+---------+--------
PASR        8  0.8767  0.0581   (-----*------)
SOTSR+PASR  8  1.0000  0.0000                         (-----*-----)
                                -+---------+---------+---------+--------
                               0.850     0.900     0.950     1.000

Pooled StDev = 0.0411


Fisher 95% Individual Confidence Intervals
All Pairwise Comparisons among Levels of Radar

Simultaneous confidence level = 95.00%


Radar = PASR subtracted from:

Radar         Lower   Center    Upper  -------+---------+---------+---------+--
SOTSR+PASR  0.07923  0.12331  0.16740                    (-------*------)
                                       -------+---------+---------+---------+--
                                            0.000     0.060     0.120     0.180
```

Figure 90. One-Way ANOVA: P(engage) vs. Radar

This boxplot in Figure 91 represents the P(kill) for each radar, with the data set including all weapon systems. In this example, the PASR + SOTSR system has a large amount of overlap with the PASR.

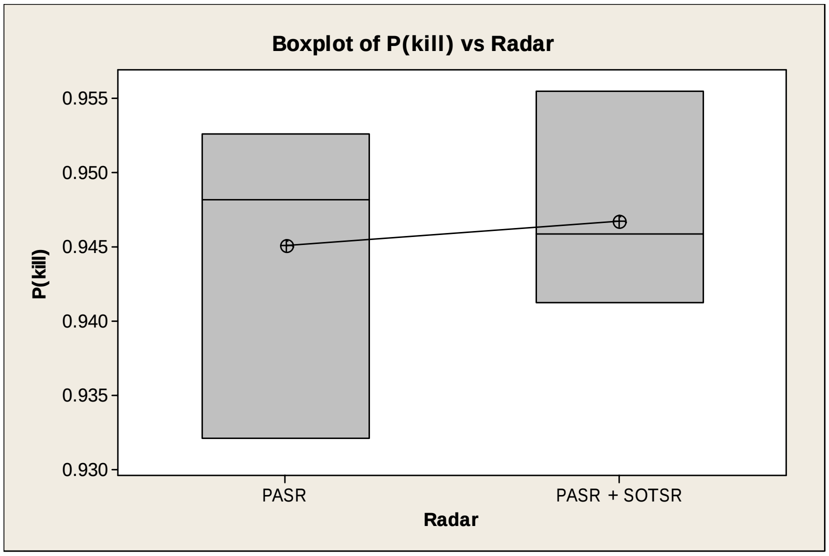
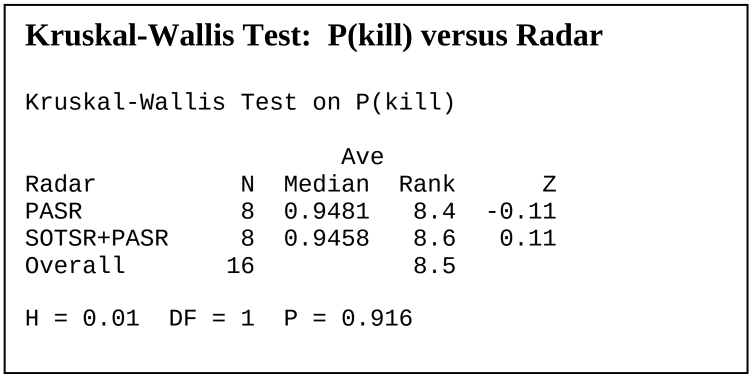


Figure 91. Boxplot of P(kill) vs. Radar

The Kruskal-Wallis analysis, Figure 92 shows that the P-value > alpha (which is the default 0.05 in this case), so there is insufficient evidence to reject the null hypothesis of equal means, and the alternative hypothesis of unequal means cannot be supported, therefore there is no statistically significant difference between the systems.



Kruskal-Wallis Test: P(kill) versus Radar

```
Kruskal-Wallis Test on P(kill)

                      Ave
Radar          N  Median  Rank       Z
PASR           8  0.9481   8.4   -0.11
SOTSR+PASR     8  0.9458   8.6    0.11
Overall       16           8.5

H = 0.01  DF = 1  P = 0.916
```

Figure 92. Kruskal-Wallis Test: P(kill) vs. Radar

The ANOVA for the radar systems is shown in Figure 93. The results show that the P-value > alpha (which is the default 0.05 in this case), so there is insufficient evidence to reject the null hypothesis of equal means, and the alternative hypothesis of unequal means cannot be supported. This indicates that the two systems do not have a statistically significant difference. Although they have different means, the differences are not statistically significant with 95% confidence. Looking at the simultaneous confidence level of the means of each system, it shows a confidence interval overlap between the two systems, meaning that they cannot be said to be different with 95% confidence.

One-way ANOVA: P(kill) versus Radar

```
Source  DF         SS         MS     F      P
Radar    1  0.0000112  0.0000112  0.28  0.604
Error   14  0.0005606  0.0000400
Total   15  0.0005718

S = 0.006328   R-Sq = 1.97%   R-Sq(adj) = 0.00%


                            Individual 95% CIs For Mean Based on
                            Pooled StDev
Level       N     Mean    StDev  ------+---------+---------+---------+---
PASR        8  0.94499  0.00748  (---------------*---------------)
SOTSR+PASR  8  0.94667  0.00491        (---------------*---------------)
                                 ------+---------+---------+---------+---
                                     0.9420    0.9450    0.9480    0.9510

Pooled StDev = 0.00633


Fisher 95% Individual Confidence Intervals
All Pairwise Comparisons among Levels of Radar

Simultaneous confidence level = 95.00%


Radar = PASR subtracted from:

Radar           Lower    Center     Upper  -------+---------+---------+---------+--
SOTSR+PASR  -0.005109  0.001677  0.008463      (----------------*----------------)
                                           -------+---------+---------+---------+--
                                               -0.0040    0.0000    0.0040    0.0080
```

Figure 93. One-Way ANOVA P(kill) vs. Radar

Figure 94 represents the probability of false alarm, based on the radar system used. A lower false alarm rate is considered desirable.

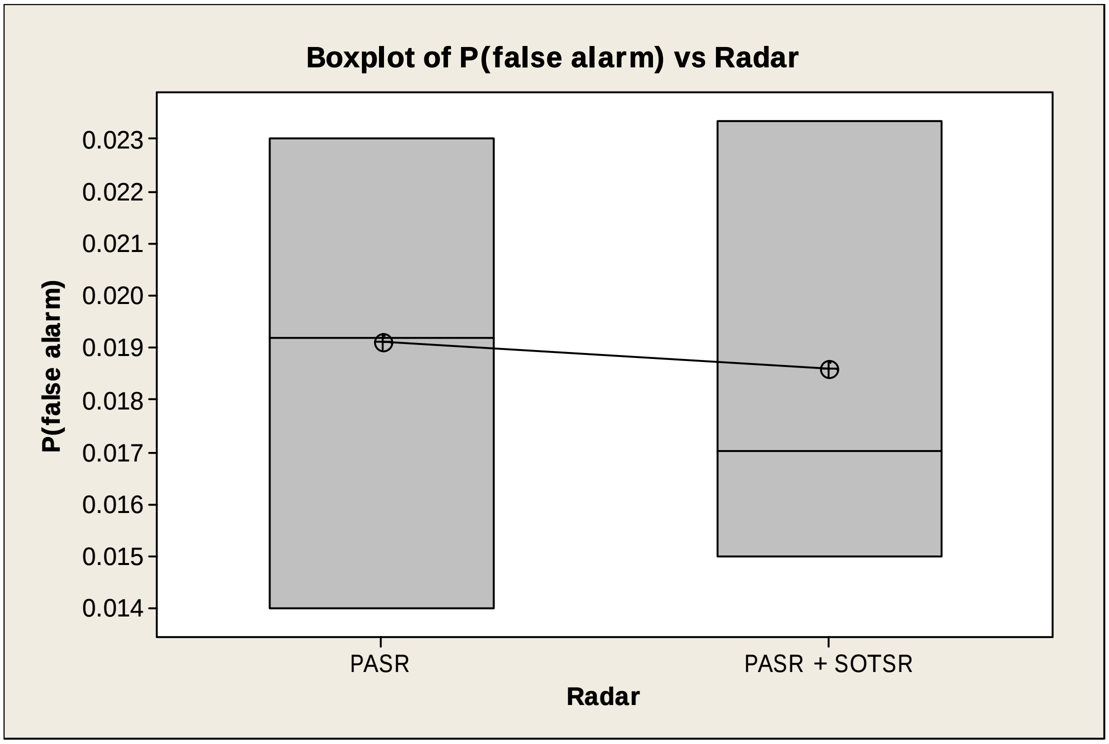


Figure 94. Boxplot of P(false alarm) vs. Radar

The Kruskal-Wallis analysis, Figure 95 shows that the P-value > alpha (which is the default 0.05 in this case), so there is insufficient evidence to reject the null hypothesis of equal means, and the alternative hypothesis of unequal means cannot be supported, therefore there is no statistically significant difference between the systems.

Kruskal-Wallis Test: P(false alarm) versus Radar

```
Kruskal-Wallis Test on P(false alarm)

                           Ave
Radar          N   Median  Rank      Z
PASR           8  0.01917   8.8   0.21
SOTSR+PASR     8  0.01700   8.3  -0.21
Overall       16            8.5

H = 0.04  DF = 1  P = 0.834
```

Figure 95. Kruskal-Wallis Test: P(false alarm) vs. Radar

The ANOVA, Figure 96, shows that the P-value > alpha (which is the default 0.05 in this case), so there is insufficient evidence to reject the null hypothesis of equal means, and the alternative hypothesis of unequal means cannot be supported. This indicates that the two systems do not have a statistically significant difference. Although they have different means, the differences are not statistically significant with 95% confidence.

One-way ANOVA: P(false alarm) versus Radar

```
Source  DF         SS         MS     F      P
Radar    1  0.0000012  0.0000012  0.10  0.758
Error   14  0.0001666  0.0000119
Total   15  0.0001678

S = 0.003450   R-Sq = 0.70%   R-Sq(adj) = 0.00%


                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level       N      Mean     StDev  ----+---------+---------+---------+-----
PASR        8  0.019125  0.003187      (----------------*----------------)
SOTSR+PASR  8  0.018583  0.003694  (----------------*----------------)
                                   ----+---------+---------+---------+-----
                                     0.0165    0.0180    0.0195    0.0210

Pooled StDev = 0.003450


Fisher 95% Individual Confidence Intervals
All Pairwise Comparisons among Levels of Radar

Simultaneous confidence level = 95.00%


Radar = PASR subtracted from:

Radar      Lower     Center     Upper
SOTSR  -0.004241  -0.000542  0.003158

Radar         -+---------+---------+---------+--------
SOTSR+PASR    (----------------*-----------------)
              -+---------+---------+---------+--------
            -0.0040   -0.0020    0.0000    0.0020
```

Figure 96. One-Way ANOVA: P(false alarm) vs. Radar

In Figure 97, this boxplot, which measures time elapsed from detection of the missile launch to BDA, uses seconds as the unit of time. The boxplots follow the same format as the previous plots, and show the PASR system as the better of the two systems, as lower Detect to BDA time is desirable, to maximize the chance of the system getting a second shot.

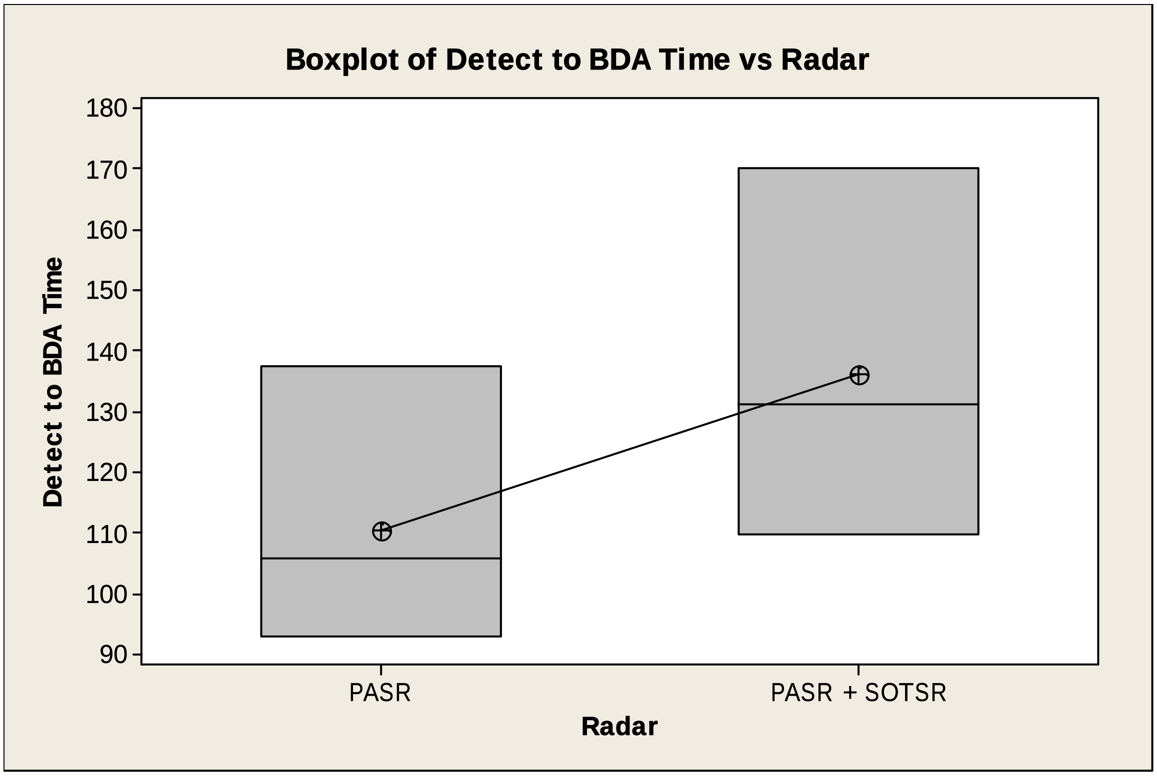
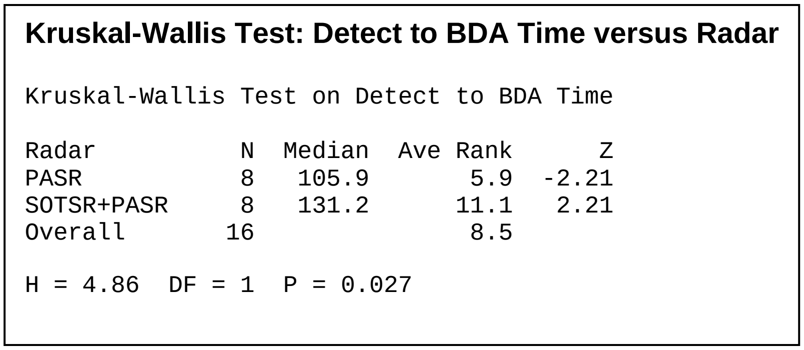


Figure 97. Boxplot of Detect to BDA Time vs. Radar

The Kruskal-Wallis analysis of the Detect to BDA time metric for each radar system is shown in Figure 98. Since the P-value < alpha (which is the default 0.05 in this case) the null hypothesis of equal means is rejected, which supports the alternative hypothesis of unequal means. This indicates that the two systems have a statistically significant difference.



Kruskal-Wallis Test: Detect to BDA Time versus Radar

```
Kruskal-Wallis Test on Detect to BDA Time

Radar           N  Median  Ave Rank      Z
PASR            8   105.9       5.9  -2.21
SOTSR+PASR      8   131.2      11.1   2.21
Overall        16               8.5

H = 4.86  DF = 1  P = 0.027
```

Figure 98. Kruskal-Wallis Test Detect to BDA Time vs. Radar

The ANOVA and Fisher CI test is shown in Figure 99. For the ANOVA, since the P-value < alpha (which is the default 0.05 in this case) the null hypothesis of equal means is rejected, which supports the alternative hypothesis of unequal means. This indicates that the two systems have a statistically significant difference. For the Fisher

CI, the interval does not include zero, so the conclusion is that with 95% confidence there is a difference between the systems, with the Phased Array radar performing better than the SOTSR.

One-way ANOVA: Detect to BDA Time versus Radar

```
Source  DF    SS    MS     F      P
Radar    1  2657  2657  7.65  0.015
Error   14  4859   347
Total   15  7516

S = 18.63   R-Sq = 35.35%   R-Sq(adj) = 30.73%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level       N    Mean  StDev  ------+---------+---------+---------+---
PASR        8  110.55  15.81  (---------*--------)
SOTSR+PSAR  8  136.32  21.08                 (---------*--------)
                              ------+---------+---------+---------+---
                                  105       120       135       150

Pooled StDev = 18.63
Fisher 95% Individual Confidence Intervals
All Pairwise Comparisons among Levels of Radar

Simultaneous confidence level = 95.00%


Radar = PASR subtracted from:

Radar       Lower  Center  Upper    +---------+---------+---------+---------
SOTSR+PSAR   5.79   25.77  45.75                 (---------*---------)
                                    +---------+---------+---------+---------
                                  -20         0        20        40
```

Figure 99. One-Way ANOVA: Detect to BDA Time vs. Radar

The boxplot of Detect to BDA time measures the time metric in seconds (Figure 100). The boxplot elements are the same for this graph as before, but now the metrics are being measured against the different weapon systems, instead of radar, so there are four boxplots, instead of two. Based on this graph, by the Detect to BDA time metric, the improved railgun weapon system is the best system, followed by the original railgun, improved missile, and finally, the original missile.

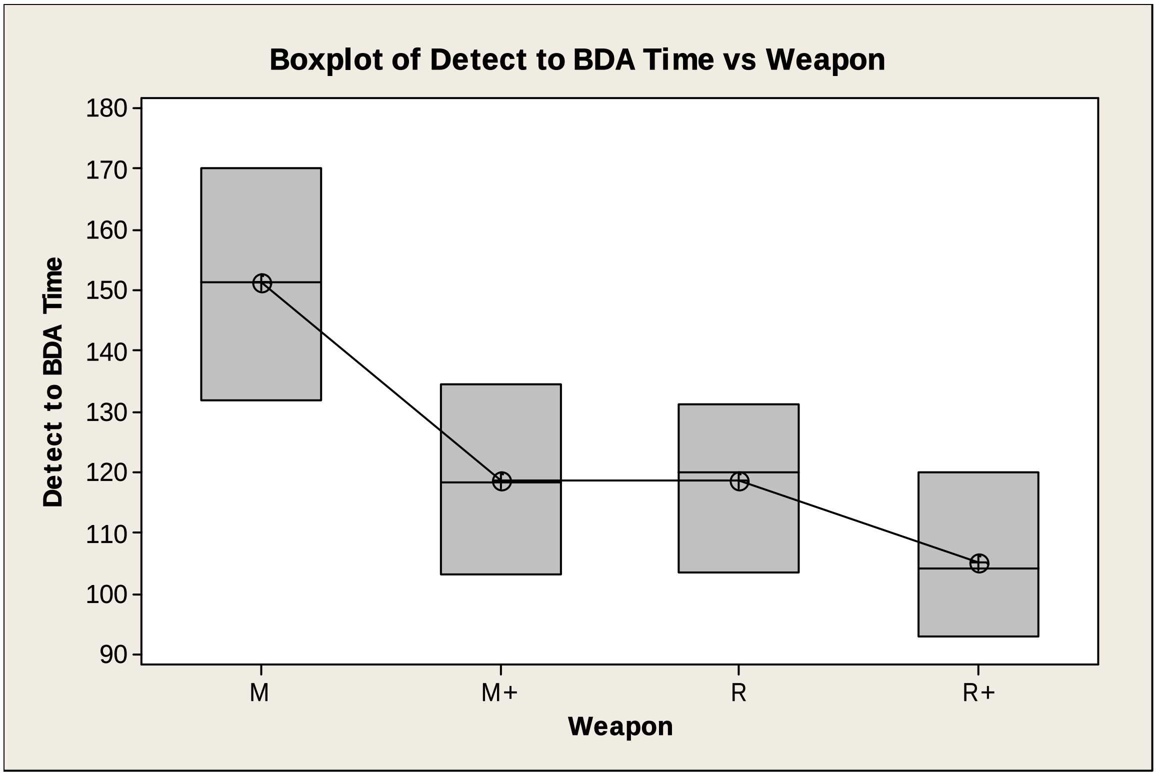


Figure 100. Boxplot of Detect to BDA Time vs. Weapon

The Kruskal-Wallis analysis is shown in Figure 101. Since the P-value < alpha (which is the default 0.05 in this case) the null hypothesis of equal means is rejected, which supports the alternative hypothesis of unequal means. However, because there are four systems, it cannot be determined which one is different by using the results of this test, just that there is a statistical difference between at least one of the systems and the rest.

Kruskal-Wallis Test: Detect to BDA Time versus Weapon

```
Kruskal-Wallis Test on Detect to BDA Time

Weapon    N  Median  Ave Rank      Z
M         4   151.4      14.3   2.79
M+        4   118.3       7.5  -0.49
R         4   119.9       7.8  -0.36
R+        4   104.1       4.5  -1.94
Overall  16               8.5

H = 8.93  DF = 3  P = 0.030
* NOTE * One or more small samples
```

Figure 101. Kruskal-Wallis Test: Detect to BDA Time vs. Weapon

For the ANOVA, Figure 102, since the P-value < alpha (which is the default 0.05 in this case) the null hypothesis of equal means is rejected, which supports the alternative hypothesis of unequal means. This indicates that one of the systems has a statistically significant difference from the others. For the Fisher CI, if the confidence interval includes zero, than it cannot be said with 95% confidence that there is a difference between the systems. The Fisher Confidence Intervals between each system has more information about which systems are different from each other. Looking at the 95% confidence interval of the missile mean, subtracted from other weapon systems means, the missile is statistically different in the Detect to BDA time metric from all other weapon systems. Next, looking at the differences with the improved missile weapon system, it is not statistically different from the railgun and improved railgun system. Finally, looking at the railgun system, it is not statistically different from the improved railgun system. Overall, the improved railgun is different than the missile, and would be the preferred system.

One-way ANOVA: Detect to BDA Time versus Weapon

```
Source  DF    SS    MS     F      P
Weapon   3  4614  1538  6.36  0.008
Error   12  2902   242
Total   15  7516

S = 15.55   R-Sq = 61.39%   R-Sq(adj) = 51.74%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  ------+---------+---------+---------+---
M      4  151.29  19.45                         (--------*-------)
M+     4  118.58  15.12         (-------*--------)
R      4  118.61  14.68         (-------*--------)
R+     4  105.25  12.05  (--------*-------)
                         ------+---------+---------+---------+---
                             100       120       140       160

Pooled StDev = 15.55


Fisher 95% Individual Confidence Intervals
All Pairwise Comparisons among Levels of Weapon

Simultaneous confidence level = 81.57%


Weapon = M subtracted from:

Weapon   Lower  Center   Upper  ---+---------+---------+---------+------
M+      -56.67  -32.71   -8.76      (-------*-------)
R       -56.64  -32.68   -8.73      (-------*-------)
R+      -70.00  -46.04  -22.08  (-------*-------)
                                ---+---------+---------+---------+------
                                 -60       -30         0        30


Weapon = M+ subtracted from:

Weapon   Lower  Center  Upper  ---+---------+---------+---------+------
R       -23.93    0.03  23.99                (-------*-------)
R+      -37.28  -13.32  10.63            (-------*-------)
                               ---+---------+---------+---------+------
                                -60       -30         0        30


Weapon = R subtracted from:

Weapon   Lower  Center  Upper  ---+---------+---------+---------+------
R+      -37.31  -13.35  10.60            (-------*-------)
                               ---+---------+---------+---------+------
                                -60       -30         0        30
```

Figure 102. One-Way ANOVA: Detect to BDA Time vs. Weapon

This boxplot measures P(kill | engagement) for each weapon, Figure 103. Because it is a conditional P(kill) based on engagement, it is testing the effectiveness of each weapon alone and not the system as a whole. For this metric, a higher number is desirable. Based on this, the improved railgun outperforms the other systems, followed in order by the railgun, improved missile, and missile.

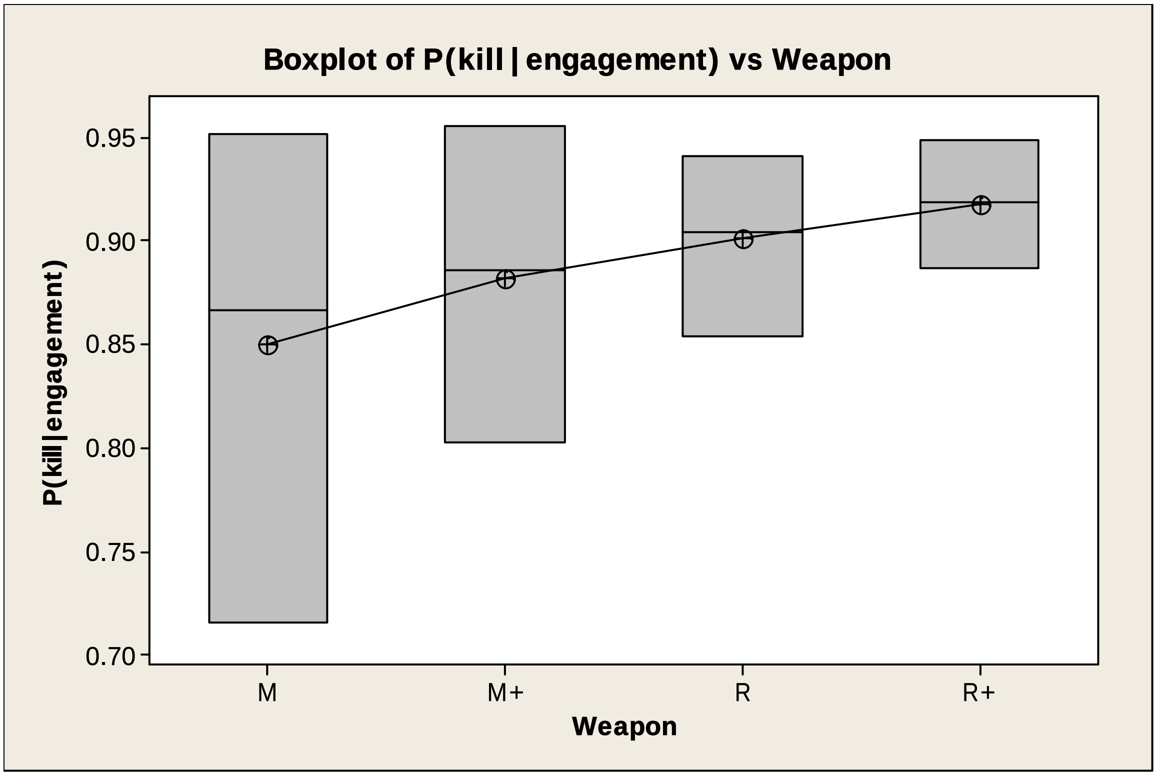


Figure 103. Boxplot of P(kill | engagement) vs. Weapon

The Kruskal-Wallis analysis of each weapon system P(kill | engagement), Figure 104 shows that the P-value > alpha (which is the default 0.05 in this case), so there is insufficient evidence to reject the null hypothesis of equal means, and the alternative hypothesis of unequal means cannot be supported., so the systems do not have a statistically significant difference.

Kruskal-Wallis Test: P(kill|engagement) versus Weapon

```
Kruskal-Wallis Test on P(kill|engagement)

Weapon    N  Median  Ave Rank      Z
M         4  0.8663       7.3  -0.61
M+        4  0.8853       8.8   0.12
R         4  0.9044       7.5  -0.49
R+        4  0.9182      10.5   0.97
Overall  16               8.5

H = 1.17  DF = 3  P = 0.760

* NOTE * One or more small samples
```

Figure 104. Kruskal-Wallis Test: P(kill | engagement) vs. Weapon

The ANOVA for P(kill | engagement) is shown in Figure 105. Since the P-value > alpha (which is the default 0.05 in this case) there is insufficient evidence to reject the null hypothesis of equal means, and the alternative hypothesis of unequal means cannot be supported. This indicates that the two systems do not have a statistically significant difference. Although they have different means, the differences are not statistically significant with 95% confidence.

One-way ANOVA: P(kill|engagement) versus Weapon

```
Source  DF       SS       MS     F      P
Weapon   3  0.01015  0.00338  0.58  0.639
Error   12  0.07002  0.00584
Total   15  0.08017

S = 0.07639   R-Sq = 12.66%   R-Sq(adj) = 0.00%


                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  --+---------+---------+---------+-------
M      4  0.8499  0.1170  (-------------*-------------)
M+     4  0.8822  0.0793       (-------------*-------------)
R      4  0.9010  0.0467          (-------------*-------------)
R+     4  0.9177  0.0343             (-------------*-------------)
                          --+---------+---------+---------+-------
                          0.780     0.840     0.900     0.960

Pooled StDev = 0.0764


Fisher 95% Individual Confidence Intervals
All Pairwise Comparisons among Levels of Weapon

Simultaneous confidence level = 81.57%


Weapon = M subtracted from:

Weapon     Lower   Center    Upper  -----+---------+---------+---------+----
M+      -0.08537  0.03232  0.15000        (-----------*-----------)
R       -0.06656  0.05113  0.16882          (-----------*-----------)
R+      -0.04986  0.06783  0.18551            (-----------*-----------)
                                    -----+---------+---------+---------+----
                                      -0.10      0.00      0.10      0.20


Weapon = M+ subtracted from:

Weapon     Lower   Center    Upper  -----+---------+---------+---------+----
R       -0.09887  0.01881  0.13650       (-----------*-----------)
R+      -0.08218  0.03551  0.15320         (-----------*----------)
                                    -----+---------+---------+---------+----
                                      -0.10      0.00      0.10      0.20


Weapon = R subtracted from:

Weapon     Lower   Center    Upper  -----+---------+---------+---------+----
R+      -0.10099  0.01670  0.13438       (-----------*----------)
                                    -----+---------+---------+---------+----
                                      -0.10      0.00      0.10      0.20
```

Figure 105. One-Way ANOVA: P (kill | engagement) vs. Weapon

5.7.3 Main Effects Plots

Using the MINITAB program, the team analyzed the Main Effects of the system model. This was done by investigating the Main Effects Plot for the following main effects: Scenario, Radar, and Weapon. The Main Effects Plot uses the shift in data mean to measure the impact of an aspect of the system model on a chosen response metric.[79]

The Main Effects Plot looks at the mean shift of different data sets for each metric. In this case, the metric used to measure data sets is Detect to BDA time (Figure 106). The mean of each data set is used, and lower numbers are desirable. First, the Main Effects Plot looks at the impact each scenario has on the metric. The stressed scenario requires more mean time for Detect to BDA time. Looking at radar, the SOTSR system requires a greater mean Detect to BDA time than the PASR system. Finally, looking at each weapon, the missile requires the most time, followed by the improved missile, the railgun, and the improved railgun.

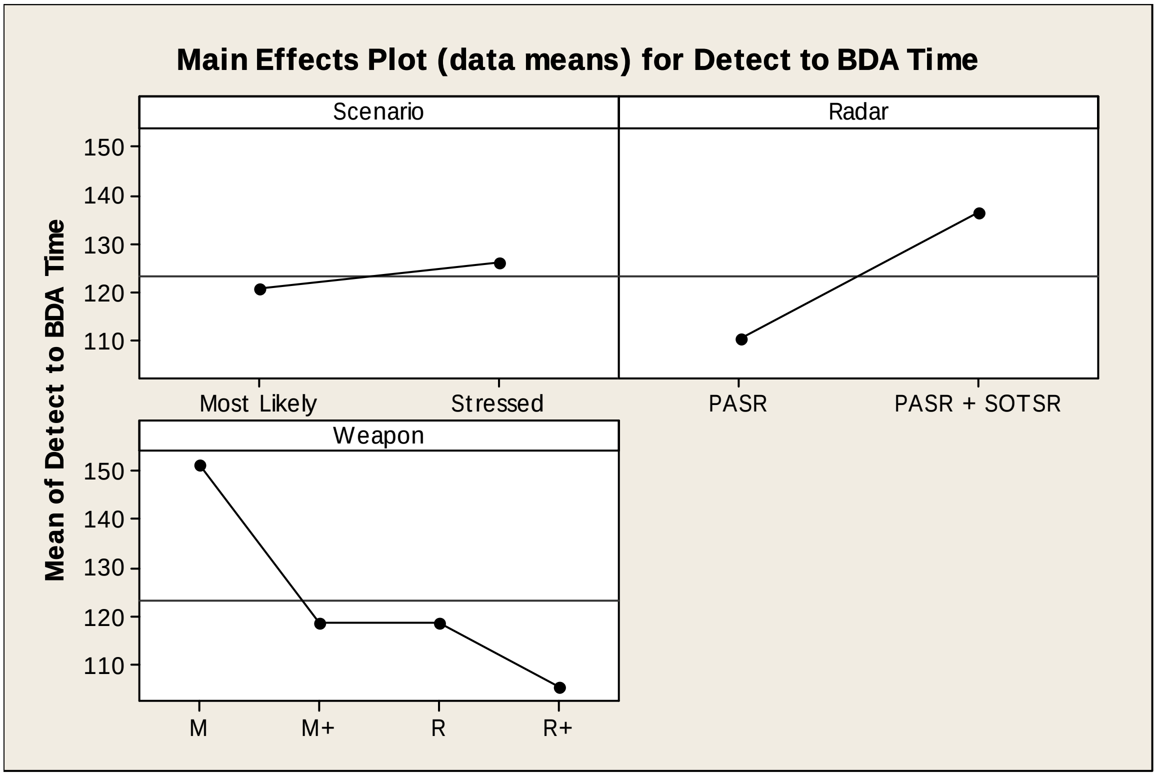


Figure 106. Main Effects Plot (data means) for Detect to BDA Time

---

[79] MINITAB, 14th Ed., "Analysis of Variance," Help-to-Go Files, http://www.minitab.com/support/docs/re114/helpfiles/statistics/AnalysisOfVariance.pdf

The main effects plot uses the same main effects as the above plot, this time to measure the metric of P(kill) with a higher number being desirable (Figure 107).

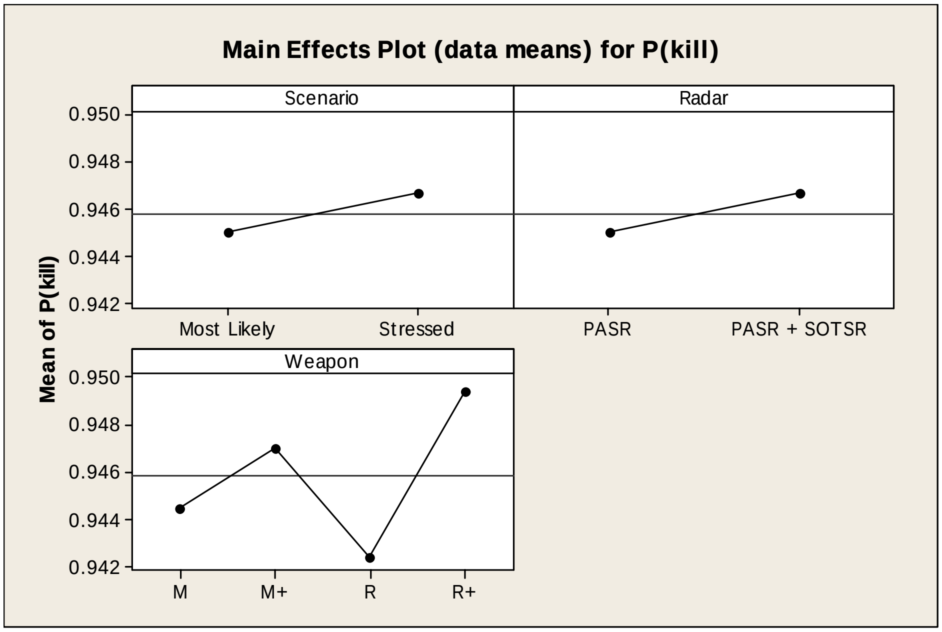


Figure 107. Main Effects Plot (data means) for P(kill)

Like the above main effects plots, scenario, radar, and weapon are used as to measure the difference in mean of a metric; in this case, P(false alarm) with smaller numbers being desirable (Figure 108).

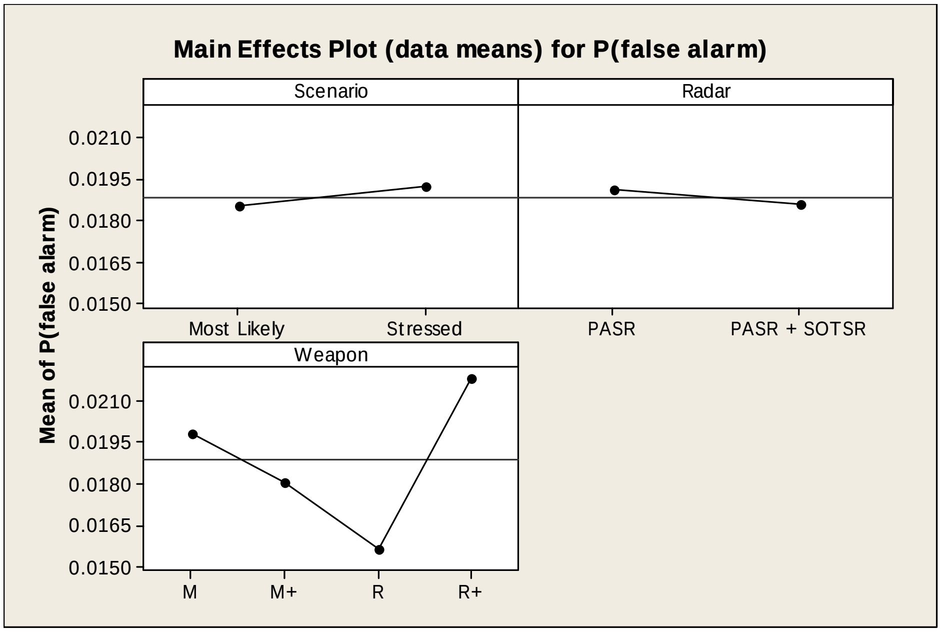


Figure 108. Main Effects Plot (data means) for P(false alarm)

This main effects plot measures the means of each main effects data set for P(engage) (Figure 109). With this metric, a higher number is more desirable, with 1.0 being the ideal.

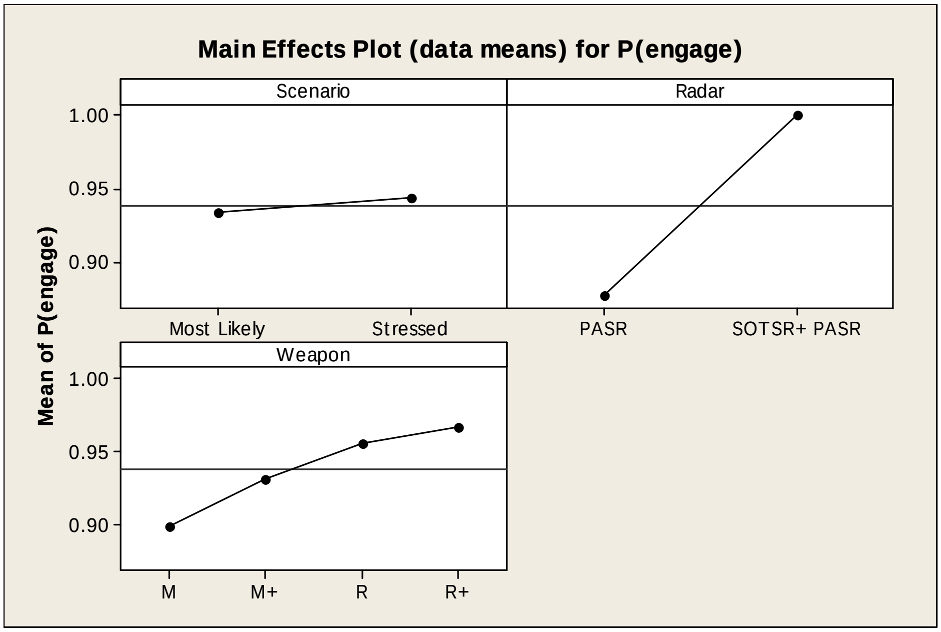


Figure 109. Main Effects Plot (data means) for P(engage)

The main effects plot measures the metric of P(handoff) for the scenario, radar, and weapon main effect, as before (Figure 110). In this metric, lower numbers are more desirable, as a handoff implies that the system failed to kill the target.

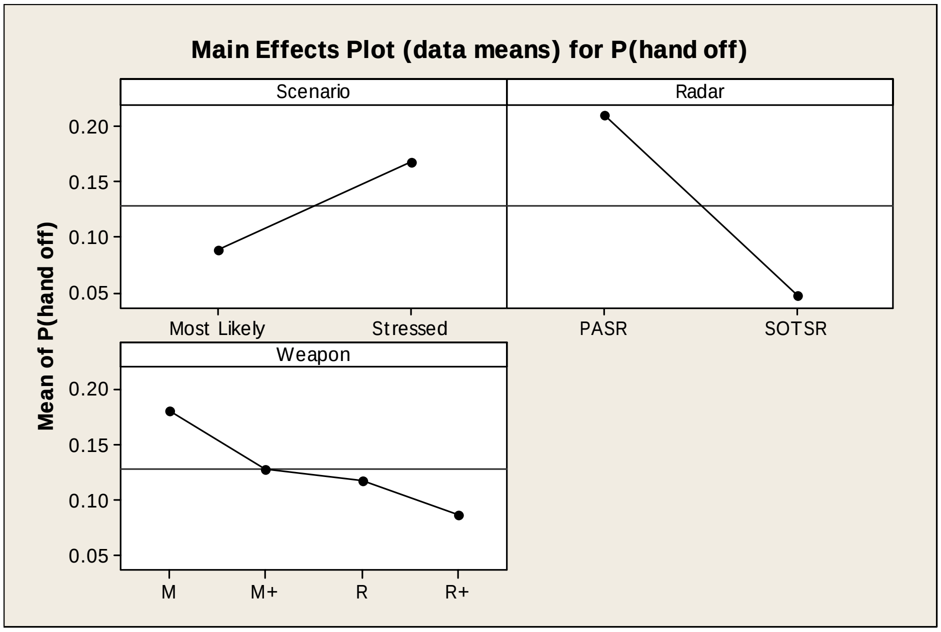


Figure 110. Main Effects Plot (data means) for P(handoff)

The metric for this main effects plot is P(detect), with higher numbers being more desirable and 1.0 being the ideal number (Figure 111).

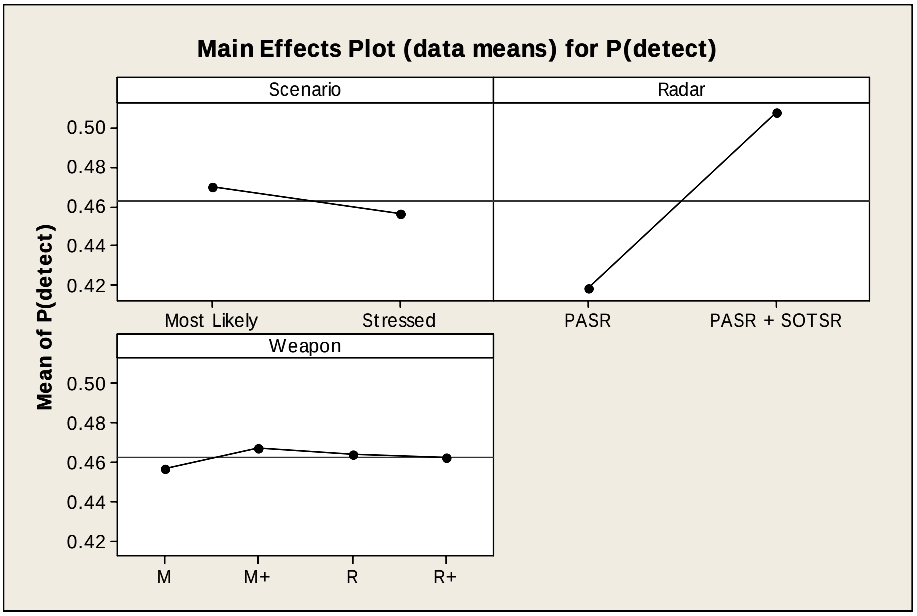


Figure 111. Main Effects Plot (data means) for P(detect)

5.7.4 Interaction Plots

Interaction Plots are a tool to look for interactions between effects in the system model. This is done because interactions between factors can have an influence on the data analysis, by introducing combinations of factors that need to be accounted for when looking at metrics. Interaction plots show that the impact that two different effects have on a response MOE to determine if the effects interact or are completely independent. If the plot lines are not parallel, that shows an interaction between effects. Completely independent factors result in parallel lines on the plot.

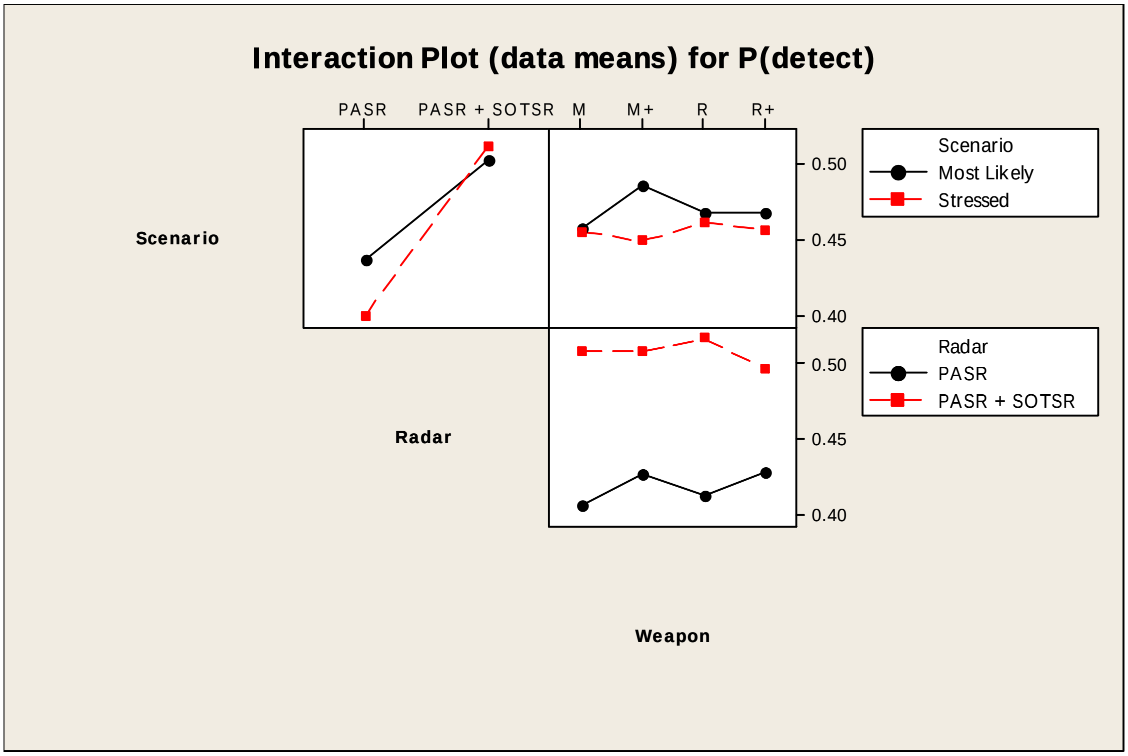


Figure 112. Interaction Plot (data means) for P(detect)

In the case of P(detect), there is interaction among all of the effects; between scenario and radar, weapon and radar, and weapon and scenario (Figure 112).

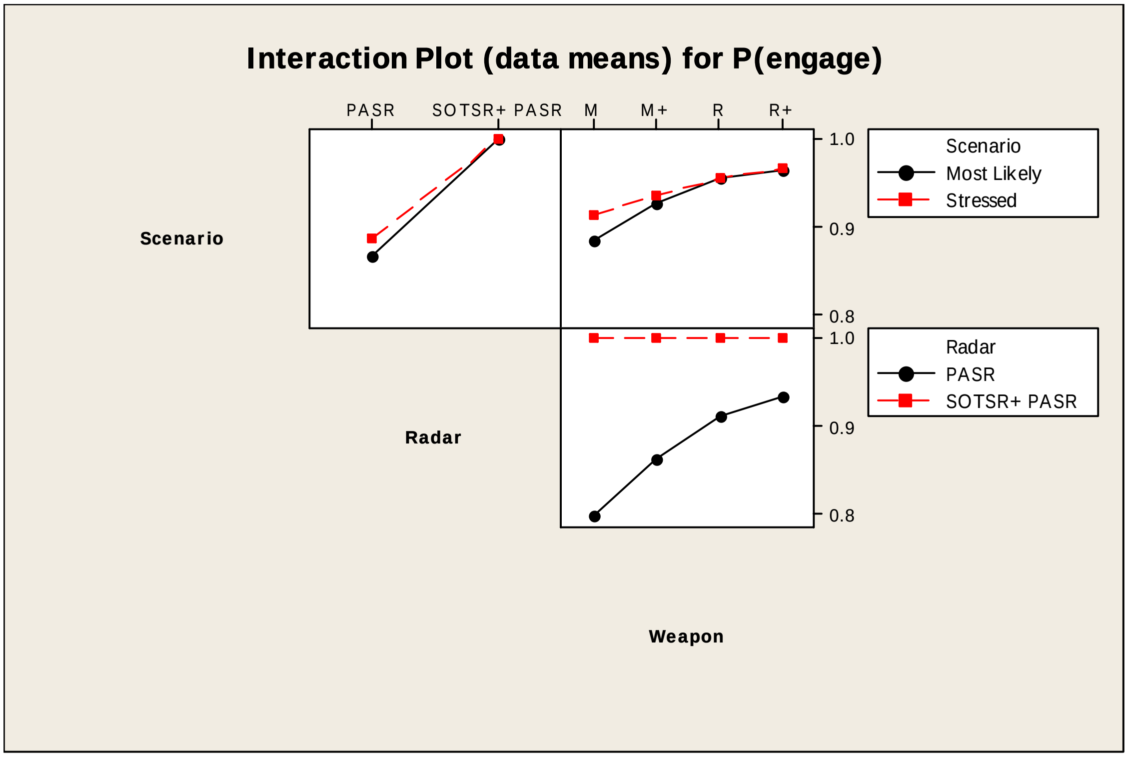


Figure 113. Interaction Plot (data means) for P(engage)

In the case of P(engage), there is interaction among all of the effects; between scenario and radar, weapon and radar, and weapon and scenario (Figure 113).

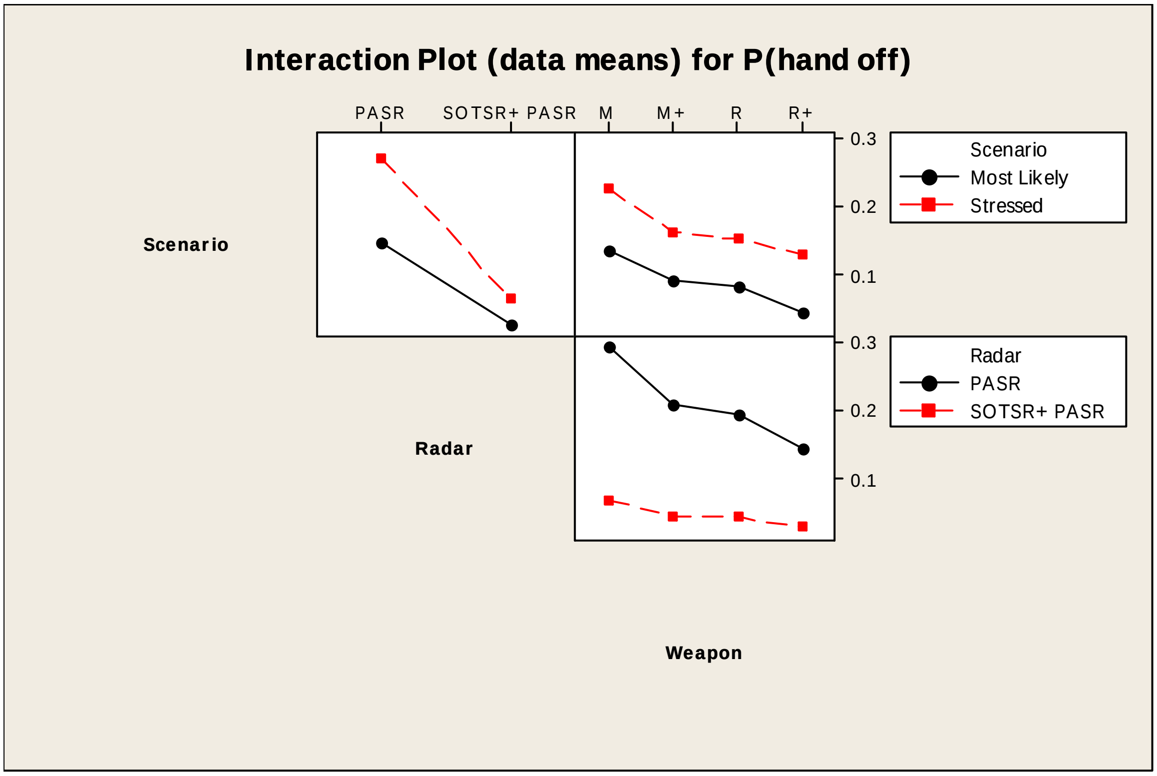


Figure 114. Interaction Plot (data means) for P(handoff)

In Figure 114, the interaction plot looks at the interactions between scenarios, radars, and weapons on the metric of P(handoff). There is no clear interaction between scenario and weapon. Interaction is evident between radar and scenario, and radar and weapon.

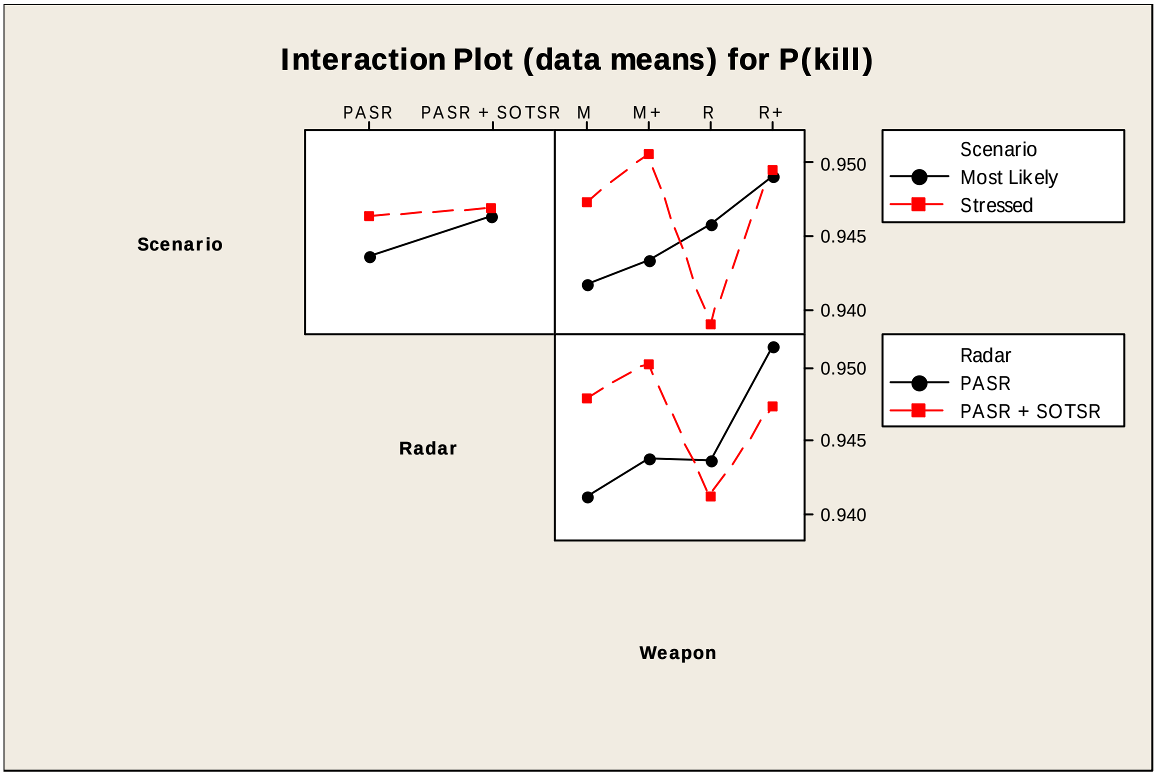


Figure 115. Interaction Plot (data means) for P(kill)

In Figure 115, the interaction plot looks at the interactions between scenarios, radars, and weapons, on the metric P(kill). These plots reveal interactions between scenario and radar, scenario and weapon, and radar and weapon.

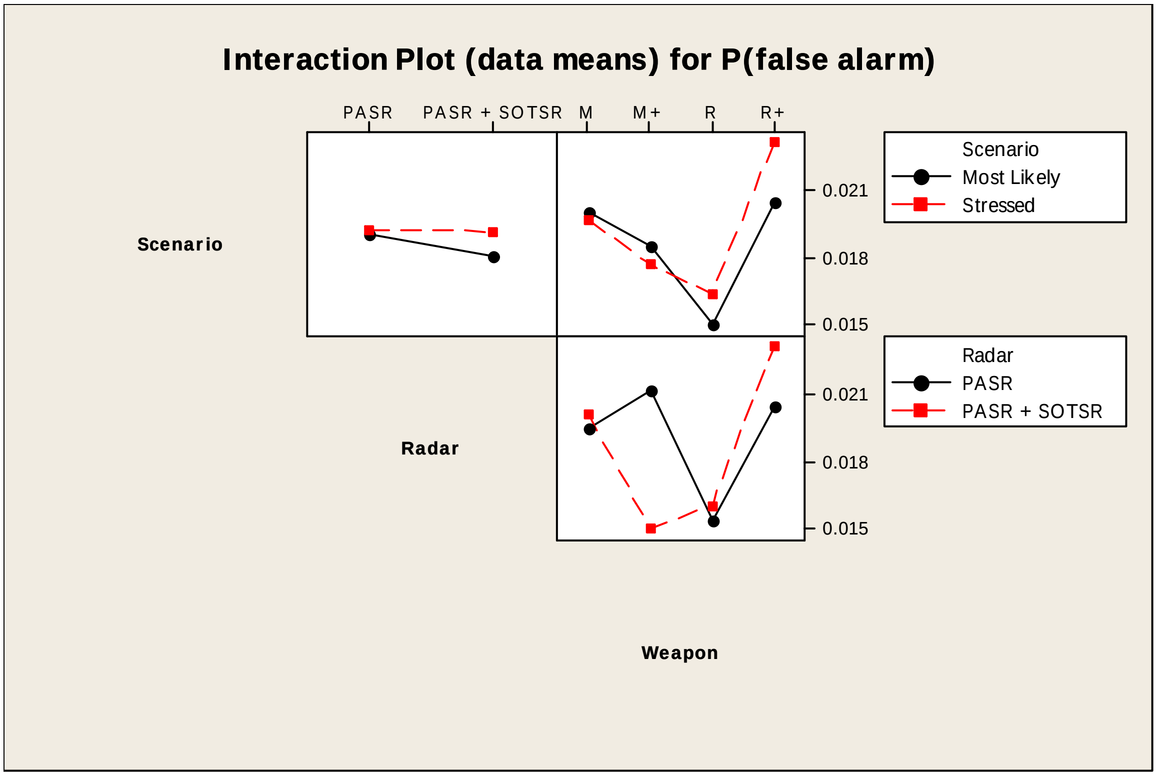


Figure 116. Interaction Plot (data means) for P(false alarm)

In Figure 116, the interaction plot looks at the interactions between scenarios, radars, and weapons, on the metric P(false alarm). In this instance, there is a clear interaction between scenario and radar, scenario and weapon, and radar and weapon.

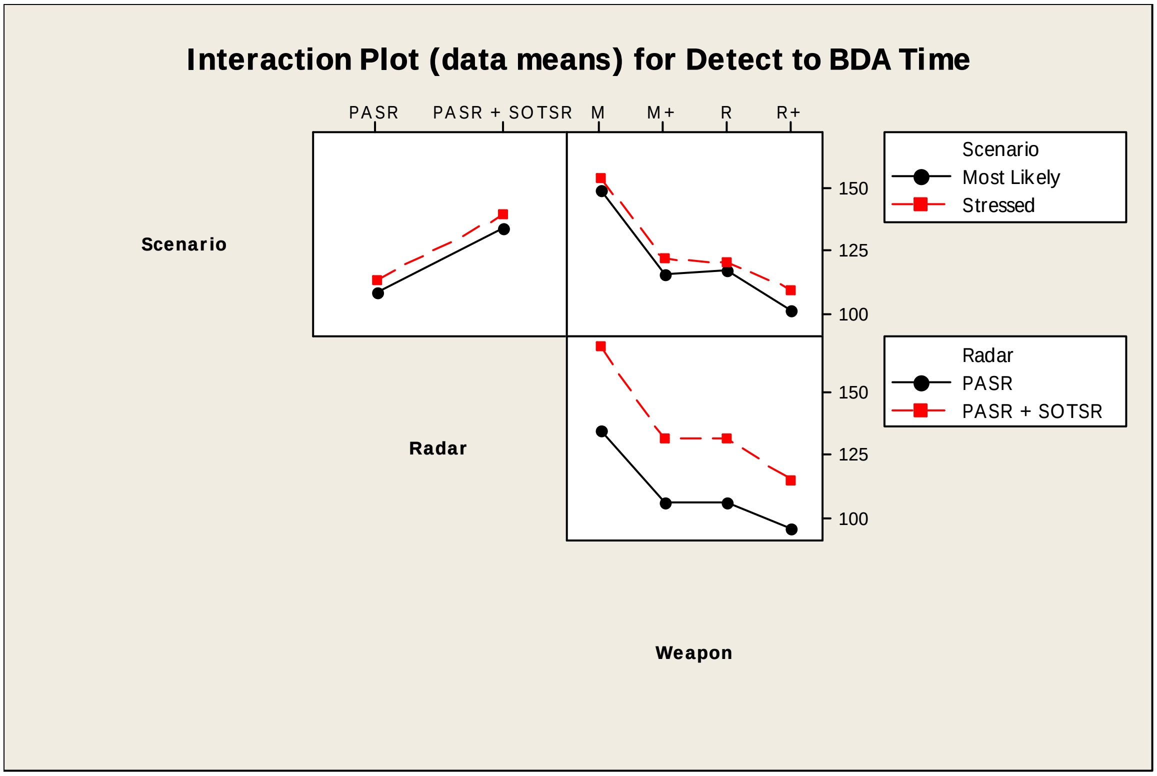


Figure 117. Interaction Plot (data means) for Detect to BDA Time

In Figure 117, the interaction plot looks at interactions between scenarios, radars, and weapons on the metric Detect to BDA Time. In this metric, there are no clear interactions between factors.

5.7.5 Conclusion

The data analysis supports the conclusion that SOTSR + PASR radar is superior to PASR individually, as well as the conclusion that the R+ interceptor system is the superior one. Table 26 shows the mean data results for different metrics.

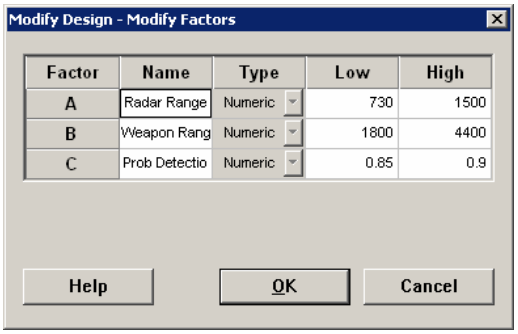
	Mean P(detect)	Mean P(engage)	Mean P(kill)	Mean P(kill | engagement)	Mean Detect to BDA (sec)
PASR	0.418	0.877	0.945		111
SOTSR + PASR	0.507	1.00	0.947		136
M				0.850	151
M+				0.882	118
R				0.901	118.6
R+				0.918	105

Table 26. Data Analysis Summary

5.8 SENSITIVITY AND TRADE-OFF ANALYSIS

The ANOVA and boxplots give insight into which combination of weapon and radar suite would yield the best performance when evaluated against the critical MOE. However, the main purpose of the SABR project study is not to specify the “best” system, but to identify a sensitivity around a set of “best” solutions in order to provide useful information for future system development direction. Therefore, a sensitivity and trade-off analysis must be done in order to identify those variables that impact the system’s overall performance with the greatest magnitude.

Since there are 18 factors, based upon the number of MOEs in the entire BMD simulation model, and each one has 2-3 levels, there are 2^{18} to 3^{18} different combinations possible to assess a full factorial experimental design. Therefore, some model order reduction had to be accomplished. From the first iteration of modeling and analysis, the system performed almost perfectly for every architecture because the parameters input to the model were set for very high performance, and as a result did not stress the system enough. Accordingly, the first set of eliminations came by eliminating the Best Case scenario. Thirteen of the factors that changed within the model were some form of scenario-based time delay. These were determined to be of lesser importance in the decision making as to the architecture configuration. These, as well as weapon velocity and probability of false alarm, were eliminated, leaving only P (detection | in range), Weapon Range, and Radar Range as the primary factors. Probability of false alarm was eliminated because it is a fixed parameter in the model that yielded no significant variability between simulations in the first and second iterations of simulations. Weapon velocity was eliminated because it was directly proportional to the weapon range. As the weapon’s velocity increased, so did its range, thereby yielding no added value to the analysis. The time delays associated with each scenario would ultimately dictate the system’s overall Probability of Detection and the Detect to BDA time. The Detect to BDA MOE was the summation of all time delays associated with the model. From the first and second iteration of modeling and analysis, it was determined that over 90% of the time that accounts for the Detect to BDA metric is spent in interceptor flight time. This makes the time delays of the detection, identification, and tracking phases very minor when compared to the interceptor flight time. This flight time is evaluated in the weapon range and Detect to BDA MOE. As discussed previously, the weapon range is proportional to weapon velocity and weapon velocity directly dictates the weapon's time of flight. Since 90% of the Detect to BDA metric is interceptor flight time, the results directly reflect each interceptor's speed as well as mean range from the targets. These factors, and their corresponding high and low levels, are depicted in Figure 118.



Factor	Name	Type	Low	High
A	Radar Range	Numeric	730	1500
B	Weapon Rang	Numeric	1800	4400
C	Prob Detectio	Numeric	0.85	0.9

Figure 118. Factor Names and Levels

The sensitivity analysis was assessed using Minitab and is depicted in a seies of Pareto charts. The Pareto charts in Figures 119-123 represent the relative importance that the various main and interaction effects have on each of the MOEs. Any effect extending past the red line has a statistically significant impact on the titled MOE. This assists in determining which effects drive an MOE to change and, therefore, allow for the focus of the design to be more efficient and effective, in order to understand the impact of factors on overall system effectiveness.

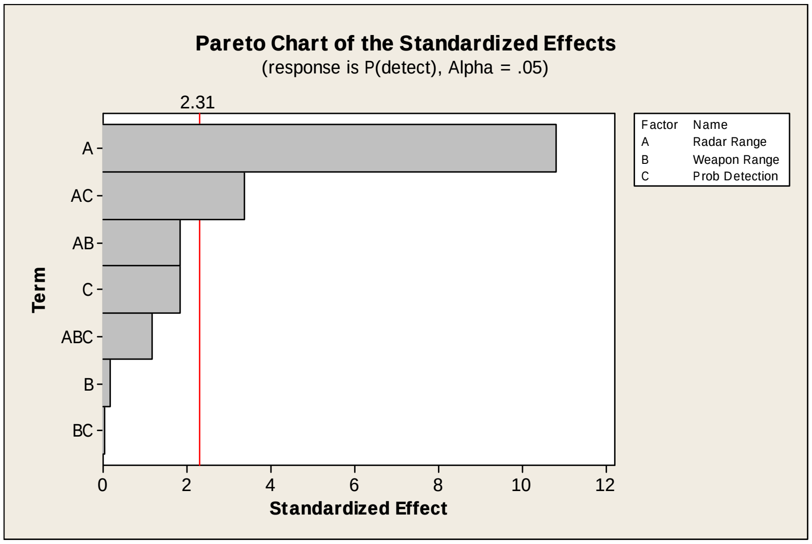


Figure 119. Pareto Chart for P(detect)

The Pareto chart in Figure 119 reveals that radar range has, by far, the greatest effect on changing the system's overall Probability of Detection. The strong leverage of radar range on the probability of detection given that the threat missile comes within range, P(detect | in range), of the radar is obvious since the in-range probability of detection will have a direct effect on the system's overall Probability of Detection. This result verifies that, indeed, the ability to detect the threat missile is driven by the radar and in-range probability of detection, rather than weapon capability.

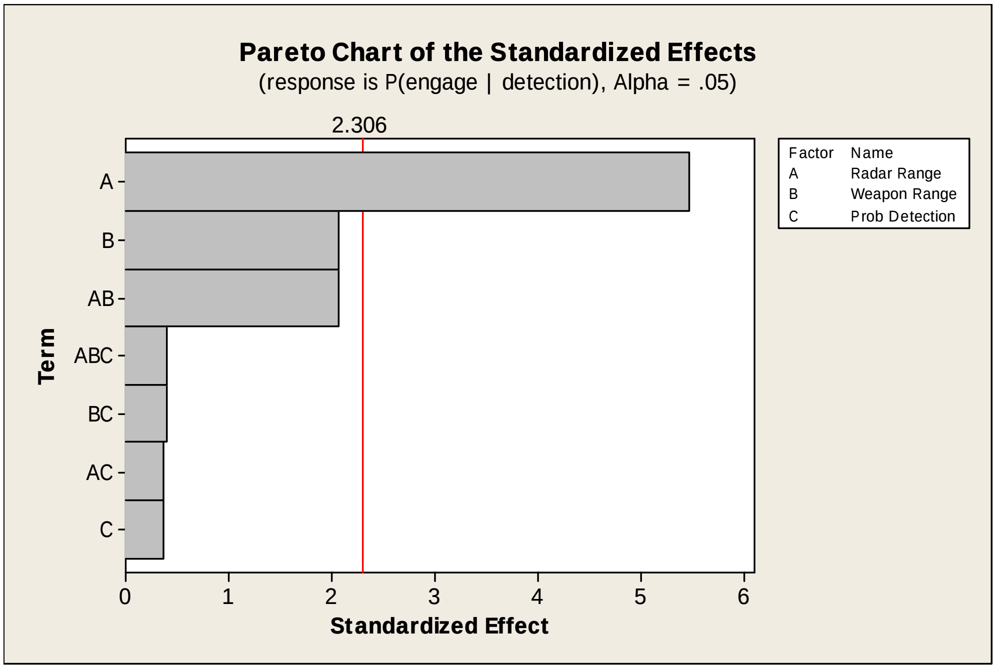


Figure 120. Pareto Chart for P(engage | detection)

Figure 120 depicts radar range as the overwhelming effect for the probability of engagement given a detection. It is important to note that it is radar range, not weapon range that dictates the level of change of engage ability. Weapon range and the interaction between weapon and radar range cannot necessarily be ignored. Though not determined to be statistically significant to the effect of probability of engagement, they are very close. Clearly, the interceptor cannot be ignored when designing a BMD platform, but as this metric shows, the radar must catch up to the capabilities of the weapon.

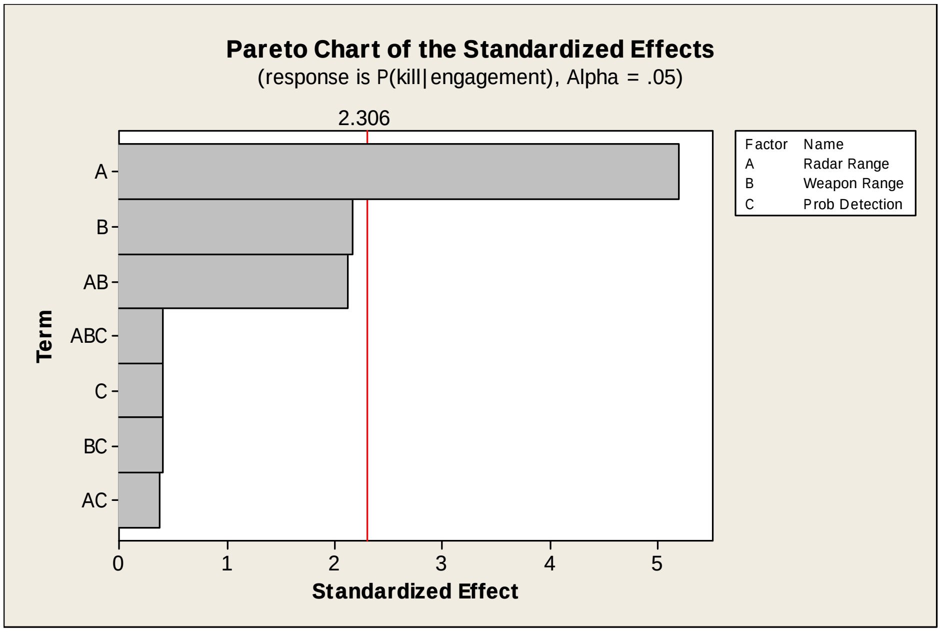


Figure 121. Pareto Chart of P(kill | engagement)

Figure 121 maintains the trend of radar range being depicted as the driving effect in each of the metric's ability to perform. Like P(engage | detection) above, probability of kill given an engagement, is dictated largely by the radar's range. However, weapon range and its interaction with radar range are very close to having a significant impact. These factors, of course, must not be ignored in the design of a BMD system.

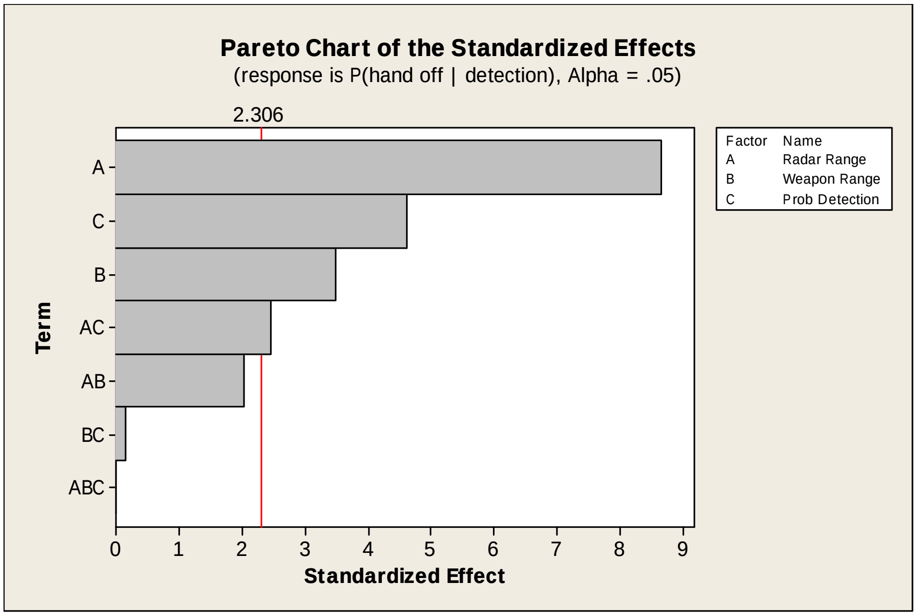


Figure 122. Pareto Chart of P(handoff | detection)

Figure 122 yields some interesting results. In the case of probability of handoff given a detection, there a four effects that were determined to have a significant impact on the system's ability to destroy the threat missile without handing off. The Pareto reveals that weapon range, radar range, probability of detection, and the interaction between radar range and probability of detection to all have a significant effect on the performance of handoffs. This makes it more difficult to focus on a factor in order to minimize the number of handoffs. This is also a expected result since the ability for the ship to handoff hinges on whether or not it detects it. So probability of detection is a reasonable factor to impact this metric. Again, radar range and weapon range are determined to be important factors. This is due to the range limitations the ranges of these factors and their capability to engage the threat missile without handing it off.

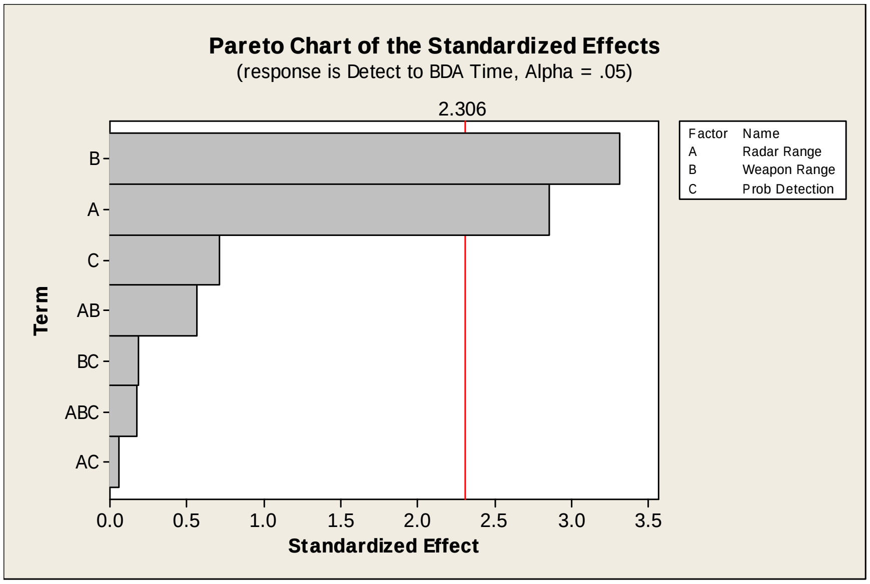


Figure 123. Pareto Chart of Detect through BDA Time

Figure 123 shows a slightly different result than has been seen in the previous MOEs. The Pareto chart shows radar range to be the driving factor to change the detection through a BDA metric. Also of significant importance is the radar's range. Both of these are fairly close in magnitude and account for a vast majority of the effect on the cycle time of the system. In order to minimize the system's engagement cycle time, the weapon and radar ranges must be the primary design considerations. This also addresses the engagement speed of the interceptor weapon, however, since the weapon range increases with increased weapon velocity, it follows that the interceptor speed must also be designed to minimize the detect to BDA time.

The sensitivity analysis shows through every Pareto chart that radar range is the controlling and limiting factor to the performance of each metric, and that weapon range is also important, but rarely statistically significant. This is due to the fact that radar range is always less than interceptor range, even at its lowest level, as noted in Figure 118. As long as the interceptor requires cueing and track data from the organic, ship based sensors, the radar range will be the constraining factor of the system. However, if the interceptors are able to receive cueing and track data from inorganic, space based sensors, then weapon range will become the limiting factor. Therefore, with the exception of probability of handoff, in order to optimize each of the measures of performance, radar and weapon range must be adjusted before probability of detection. These significant effects to MOE performance are summarized in Table 27. For a time-distance problem such as missile defense, the faster and farther these ranges can be, the better the measures of performance will be. These factors will continue to mature and be limited by time and technological advancement.

MOE Factor	P(detect)	P(engage | detection)	P(kill | engagement)	P(handoff | detection)	Detect to BDA Time
Radar Range	X	X	X	X	X
Weapon Range				X	X
Prob. Detection if in Range				X	
Radar Range and Prob. Detection	X			X	

Table 27. Significant Effects for MOE performance

5.8.1 Trade-Off Analysis

From the sensitivity analysis, the most influential factors for each of the MOEs were revealed. The trade-off analysis seeks to adjust those factors in order to find an optimal set of levels that satisfies the systems requirement as well as the customer’s needs, including cost.

Figures 124 and 125 depict contour plots of each P(kill | engagement) and P(handoff | detection) for the system. These plots verify the same results as sensitivity analysis in terms of an MOE’s sensitivity to a change in factor level, but allow the user to pick any value for two of the three metrics and determine how well the MOE is met for those two values. Those plots with virtually straight vertical or horizontal shades indicate that MOE is fairly insensitive to a change in of the respective factors.

Figure 124 depicts a contour plot for the probability of kill given an engagement MOE. The three graphs show the combinations of the three factors against how well probability of kill performs for any two values of radar range, weapon range, or probability of detection, while the different colors represent different achievable values of the probability of kill metric.

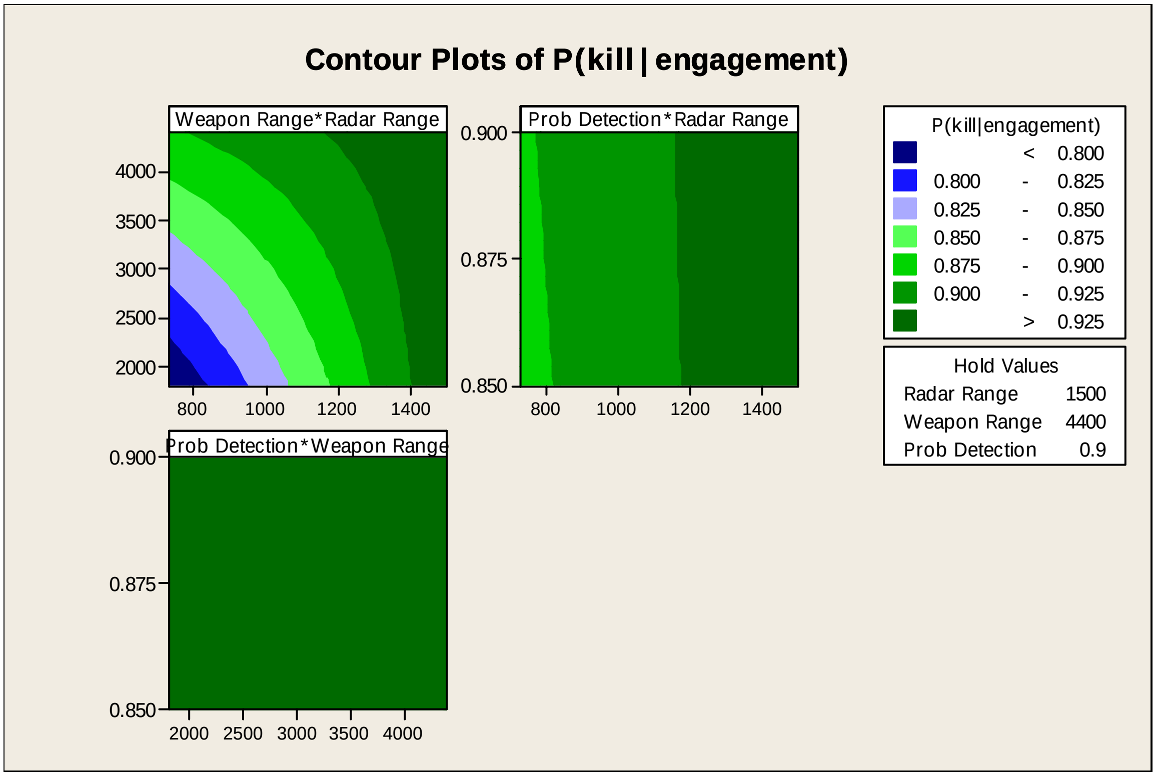


Figure 124. Contour Plot of P(kill | engagement)

The "Weapon Range*Radar Range" graph shows that probability of kill is fairly sensitive to a change in either weapon range or radar range. However, it is more responsive and can get better overall performance by maximizing the radar range. The decision to design to either radar range or weapon range will be a factor of cost and achievable technology.

Figure 125 depicts a contour plot for the probability of hand off given a detection MOE. As in the P(kill) contour plot, these three graphs also show the combinations of the three factors against how well probability of handoff performs for any two values of radar range, weapon range, or probability of detection. This metric appears much more sensitive to a change in the three factors with probability of kill. Probability of handoff is sensitive to a change in all three factors. This was also noted in the sensitivity analysis to be affected by radar and weapon range, probability of detection, as well as an interaction between radar range and probability of detection. For example, the system will perform with a probability of handoff of 0.03-0.06 with a probability of detection of 0.875 and a weapon range of 3,000 km. However, it will take an increase in weapon range to 4,500 km to achieve a probability of hand off of <0.03, whereas it would only require an increase in probability of detection to 0.9 to achieve a probability of handoff of <0.03 for the same weapon range of 3,000 km. This shows that the probability of handoff is fairly insensitive to a change in weapon range and very sensitive to probability of detection and radar range.

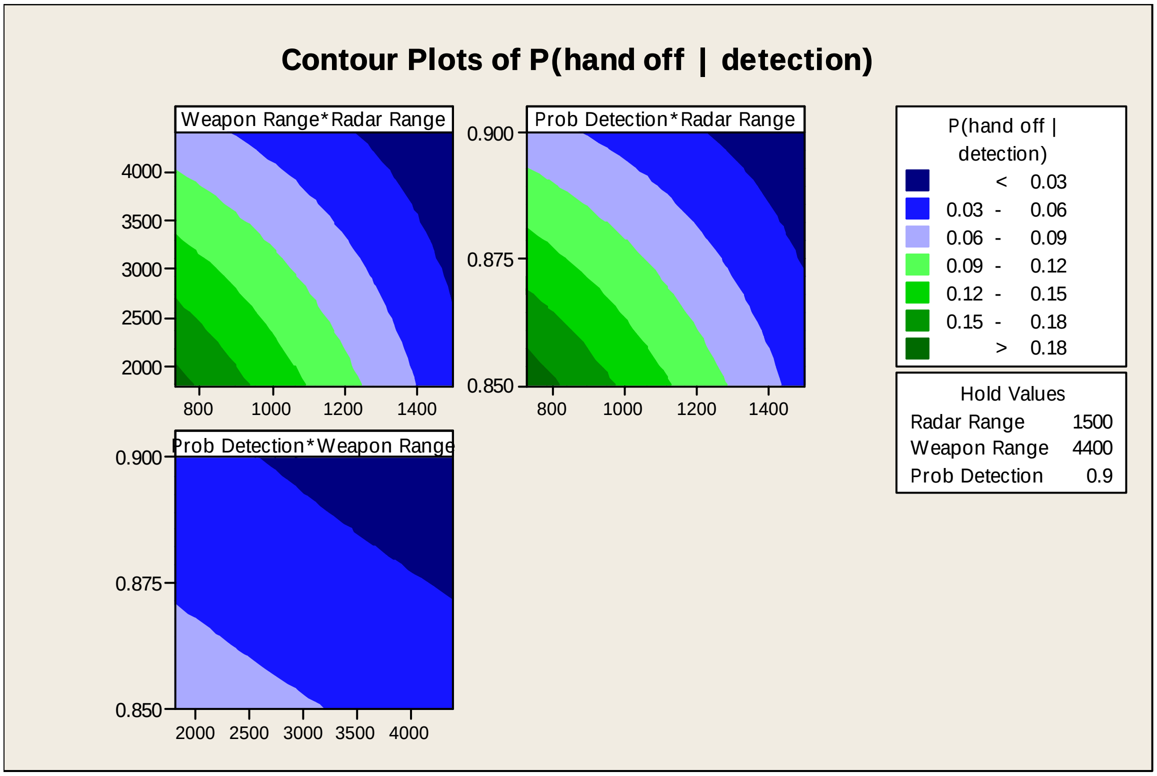


Figure 125. Contour Plot of P(handoff | detection)

To show the utility of the contour plots, the chart for P(kill | engagement) in Figure 126 will be used to determine some tradeoffs for the system's effectiveness in terms of probability of kill, while trading off performance in radar and weapon range. If a weapon range of 3,000 km can be achieved with a radar range of 1,200 km, the system will respond with a P(kill) of 0.875. However, if a higher Pk is needed, a stakeholder could choose to trade 500 km of weapon range (weapon range = 2,500 km) for a gain of 100 km in radar range in order to achieve a P(kill) of 0.9. Any set of weapon and radar ranges that intersect in the second shade of green, as noted in the chart legend, will yield a P(kill) of 0.9. This method works for all MOEs and the factors that drive their performance. This information can then be applied to cost to determine whether or not a level of performance is technically and financially feasible to the designer and stakeholder.

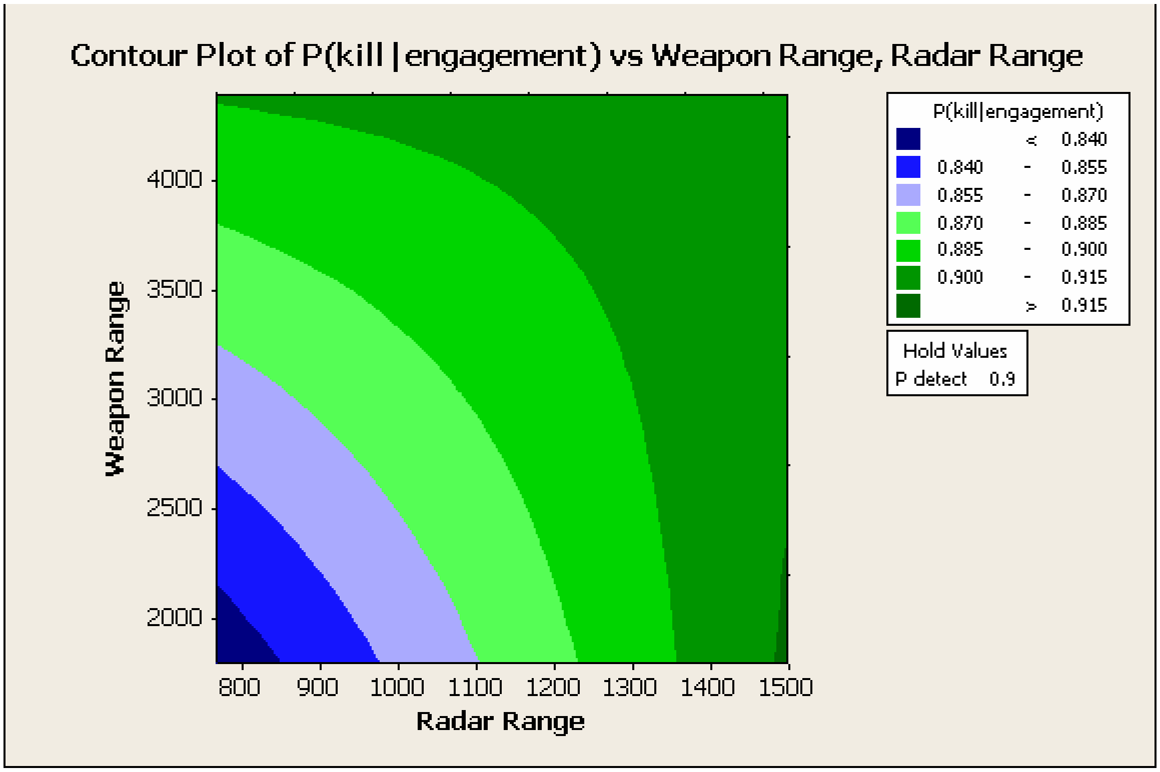


Figure 126. Contour Plot of P(kill | engagement) Against Radar and Weapon Range

5.8.2 Cost Analysis

Contour plots are a very useful tool for top-level decision makers to quickly understand how the MOE output responses change. The value added is that stakeholders can interactively determine the impact of increasing or decreasing the factors without having to run simulation cases. These plots allow for stakeholders to determine which factors are worth investing in and which are not. This trade-off analysis confirms the conclusions of the sensitivity analysis—that the radar and weapon range are the influencing factors to the MOPs. They must be the factors to design to and invest in when the shipboard BMD platform comes to fruition.

Unlike this project, the world of design and fabrication is constrained by financial means and stakeholder interest. Understanding the most influential factors and the tradeoffs associated with them now allows the real constraint on money to be applied to them. Designing the best possible technically performing system is almost never an option, but designing the best performing system for the money is. In Table 28 and Figure 127, the tradeoffs between cost and MOE for each architecture are depicted. Using the table and figure allows a designer or stakeholder to pick a level of performance from the contour plots and determine whether or not it is financially feasible to design the system. These plots are based on the costing figures in the Cost Estimation section of this report and are summarized in Table 28. These cost figures also include a cost figure for a surplus of 100 rounds for each weapon architecture, rather than only the cost of a single round. This gives a more feasible cost figure to analyze with the other components of the overall architecture. The estimates also include the developmental, construction, and fitting costs for each architecture component.

Architecture	**Weapon Cost ($M)**	**100 Target Cost ($M)**	**Radar Cost ($M)**	**Total Cost ($M)**
PASR w/ 6km/s Missile (M)	$0.41	$41.00	$40.00	**$81.00**
PASR w/ 8km/s Missile (M+)	$11.30	$1,130.00	$40.00	**$1,170.00**
PASR w/ 8km/s Railgun (R)	$0.03	$9.00	$40.00	**$49.00**
PASR w/ 10km/s Railgun (R+)	$0.06	$18.00	$40.00	**$58.00**
SOTSR w/ 6km/s Missile (M)	$0.41	$41.00	$130.00	**$171.00**
SOTSR w/ 8km/s Missile (M+)	$11.30	$1,130.00	$130.00	**$1,260.00**
SOTSR w/ 8km/s Railgun (R)	$0.03	$9.00	$130.00	**$139.00**
SOTSR w/ 10km/s Railgun (R+)	$0.06	$18.00	$130.00	**$148.00**

Table 28. Architecture Cost Estimates

Figure 127 is formatted to show Cost as an Independent Variable (CAIV) as a tradeoff of P(kill | engagement). CAIV takes a cost-based approach to designing. Rather than designing to a level of performance and paying what is needed, the CAIV approach designs to a cost and gets the best possible performance for the money. Figure 127 shows that the 8km/s missile (M+) is always the most financially undesirable option due to its high unit cost, and also depicts the dominated architectures for the probability of kill metric. A dominated architecture is essentially getting less performance for the cost. It is depicted by any point that is right and below any other point. Although the 6 km/s missile (M) and the railgun (R and R+) architectures are close in performance and cost, the SOTSR architectures provide the best performance for a small increase in cost.

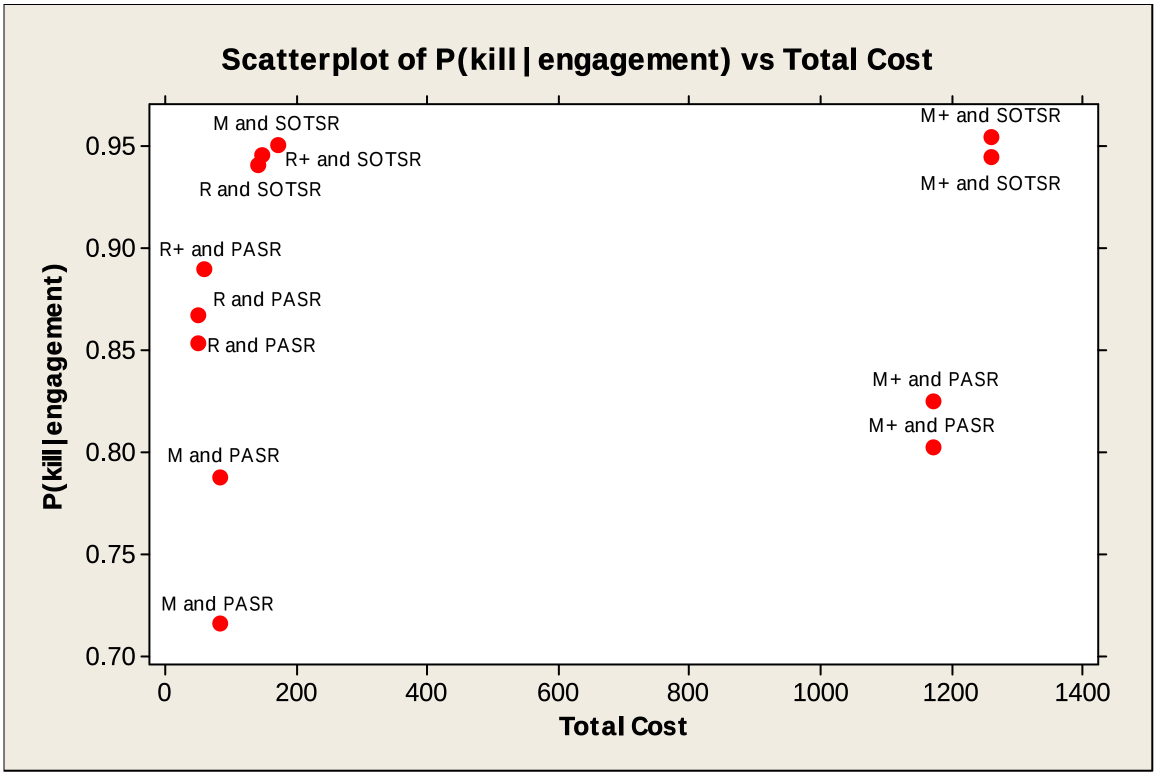
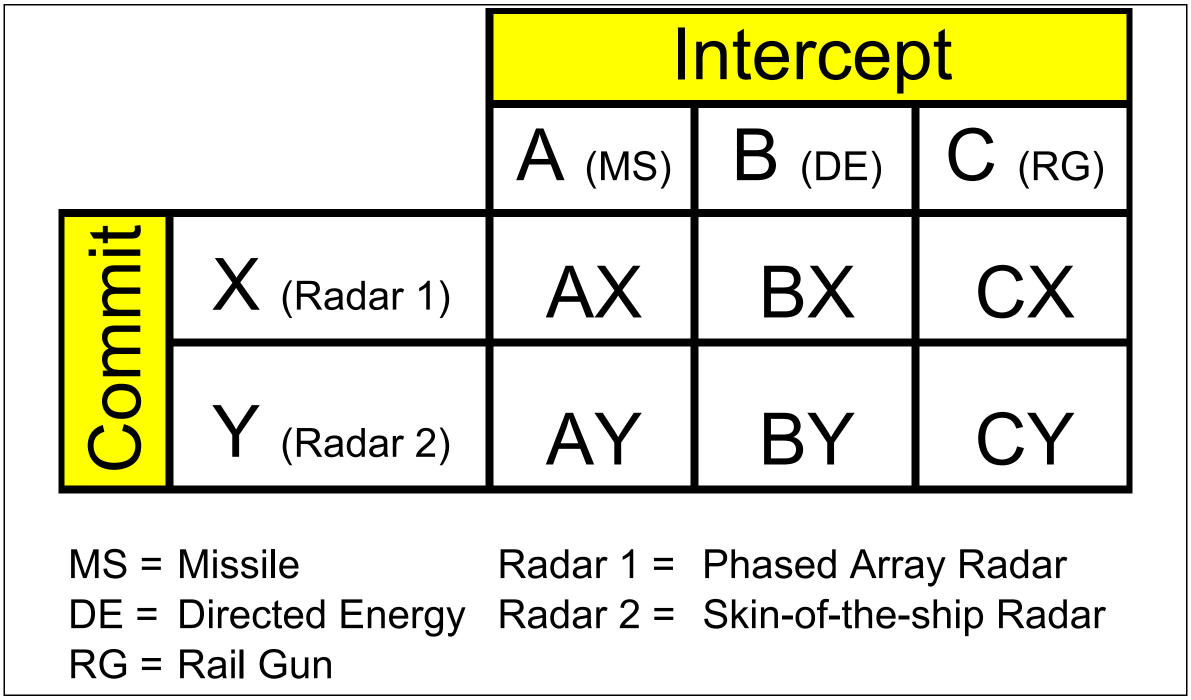


Figure 127. CAIV Plot for P(kill | engagement)

In terms of performance and cost, the 10 km/s railgun, in addition to the SOTS-assisted PASR (R+ and SOTSR), is the most feasible and efficient architecture.

5.9 SUMMARY OF REFINED DATA

The results from the "Refined Data" stage of this project charts the course for the remainder of the SABR project. Going into this stage of the project, six different "Alternative Architectures" were considered (Figure 128).



		Intercept		
		A (MS)	B (DE)	C (RG)
Commit	X (Radar 1)	AX	BX	CX
	Y (Radar 2)	AY	BY	CY

MS = Missile
DE = Directed Energy
RG = Rail Gun

Radar 1 = Phased Array Radar
Radar 2 = Skin-of-the-ship Radar

Figure 128. Proposed Alternative Architectures

Based on data results, the DEW is eliminated. This was due to high cost and relatively short effective ranges.

The missile and railgun interceptors show very similar performance characteristics. Additionally, the radars have been compared. In this case, the performance of the SOTSR complementing a PASR was shown to be superior to the stand-alone PASR.

The final preferred architecture selected for further analysis is the railgun interceptor supported by the SOTSR detection system, architecture **CY**. The remainder of this report is centered on this combination of subsystems.

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6.0 SYSTEM SYNTHESIS AND EVALUATION

6.1 SYSTEM SYNTHESIS/FINAL ARCHITECTURE

All of the preliminary modeling data was analyzed in order to find the most effective radar and weapon that could be paired together to meet the needs and requirements of the SABR project BMD system. Data analysis allowed the team to conceptualize a final BMD architecture utilizing a SOTSR assisted phased array radar in conjunction with a railgun weapons system, and model it against several different scenarios that could substantiate plausibly feasible emerging threats. In this section, detail will be provided into the development of the final preferred architecture, the plausible emerging threat scenarios, and the modeling entailed. This section also covers cost comparisons between current BMD systems and the SABR project's preferred final architecture, and the resulting analysis of the performance of the preferred architecture in the different emerging threat scenarios.

6.1.1 Final Architecture

The final system chosen consists of a Multifunction Phased Array Radar (MFPAR), a SOTSR, and a ship-based railgun weapon system.

The ship's MFPAR will be able to provide dedicated search, track and fire control and missile guidance capabilities simultaneously, which will contribute to the BMD mission of the ship. By itself, the MFPAR will have a detection range of 772 km in surveillance mode, and a maximum range of 971 km when in tracking mode. However, the ship's radar will not entirely depend on the MFPAR; that system is augmented with a SOTSR, which may consist of up to 1,200 elements on the hull of the ship, and has the potential to increase the detection range of a 10 m^2 object to over 2,000 km. In addition to all the organic sensors, there will be nonorganic land- and space-based radar systems that will provide early cueing to the system.

The second main part of the system is the interceptor, or the railgun launcher, which is also ship-based. The railgun must be capable of launching 12-16 guided rounds per minute, with 2-kg rounds achieving a velocity of 10 m/s, with a range of over 4,400 km in order to meet worst case scenario requirements.

6.1.2 Scenarios

6.1.2.1 Overview

In light of the multitude of threat nations, terrorist organizations, and other credible factions that pose a plausible BM threat to the United States and its allies, and their deployed forces, four BMD scenarios were developed to encompass the following realistic factors:

- Number of launch sites at various ranges and bearings from deployed BMD ships
- Number of targets at various ranges and bearings from deployed BMD ships
- Number of BMs simultaneously in flight (which include BM quantities greater and less than the BMD ship's probable simultaneous engagement capability)
- Environmental conditions
- BM flight profiles in relation to deployed BMD ships (closing, crossing, and tail-chase)
- Geographic challenges (mountain ranges, straits, peninsulas, gulfs, etc.)
- Approximation of operational "hot spots" as context for scenarios

The purpose of the scenarios is to place the conceptual system in simulated operational situations to "flex" system capability and measure the effectiveness of the basic concept of operations (CONOPS) (operational employment) of the system.

6.1.2.2 Four Scenarios

Four scenarios were developed for systems evaluation. The first scenario, or Functional Scenario, was developed to test system functionality. Scenarios 2, 3, and 4 were developed to test the system or system of systems under operational circumstances. These last three scenarios are titled East Asian, Middle Eastern, and Sea Base defense scenarios, respectively.

6.1.2.2.1 Functional Scenario. This scenario was developed to test the functionality of the conceptual BMD system. Operational employment is three ships providing defense for six known targets from three known launch sites. The ships are strategically placed in a central location in relation to the launch and target sites. Targets include five land targets and one sea target. BM launch sites, intended impact sites (targets), and ship position are shown in Figure 129 (launch site indicators, targets, and ship sizes are not to scale).

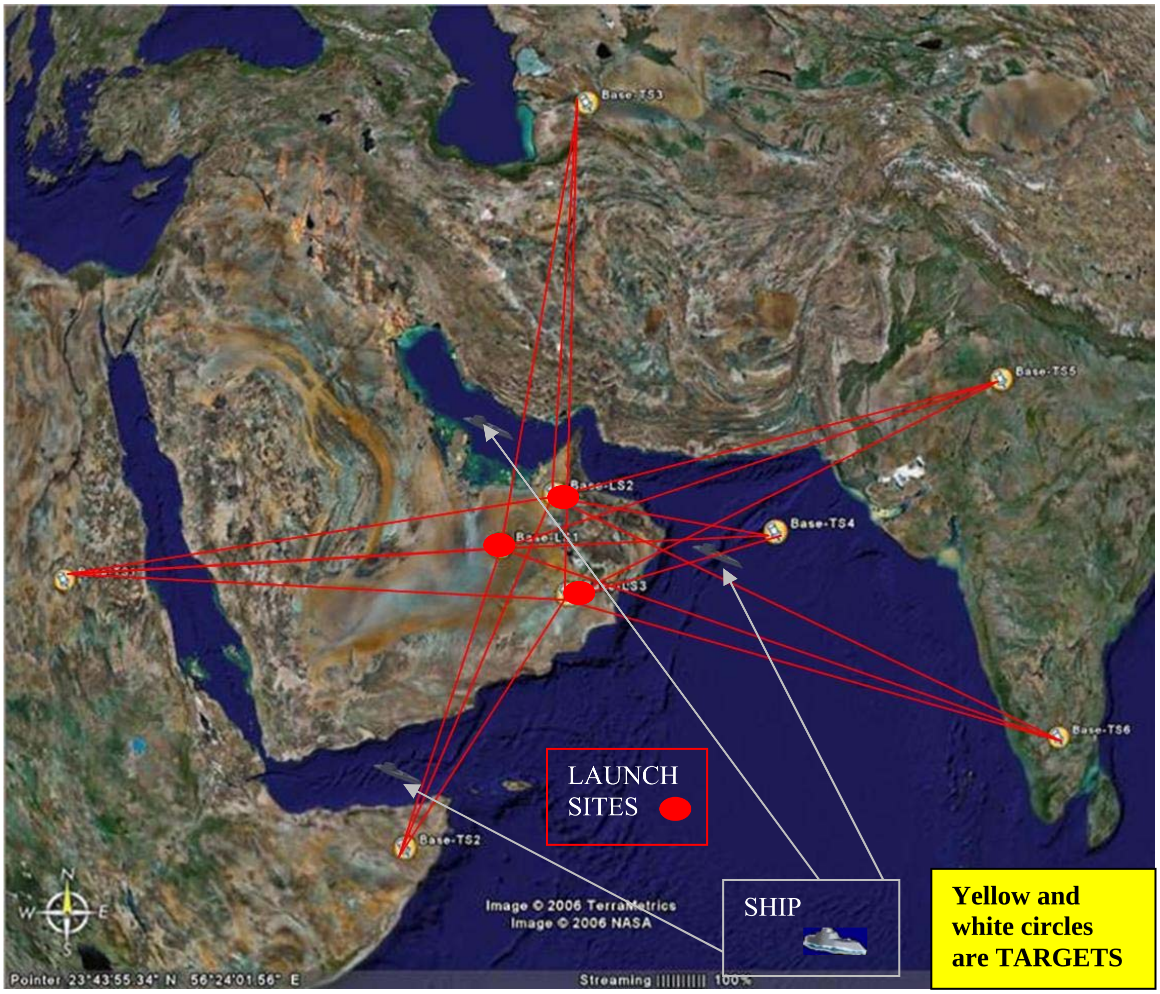

Figure 129. Functional Scenario

In each salvo (model run) any combination of one, two, or all launch sites can fire approximately 23-33 BMs (totaling 70-100 BMs in simultaneous flight) to various targets. Each salvo is independent of one another and inventories of both BMs and interceptor rounds are replenished prior to start of each successive salvo. The number of active launch sites, BMs launched per launch site, and ultimate targets of launched BMs are random to eliminate any learning curve of the system.

Table 29 indicates the distances between launch and target sites in *kilometers*. To improve accuracy for input into the threat model, distances were measured using an automatic grid position, a manual measurement grid position, and using Great Circle routes.

Launch Site	Target Site	Auto Grid	Manual Grid	Great Circle
1	1	2,161.672	2,132.640	2,141.945
1	2	1,429.823	1,424.710	1,427.418
1	3	1,986.790	1,984.950	1,991.373
1	4	1,162.730	1,160.315	1,164.738
1	5	2,328.557	2,360.620	2,373.016
1	6	2,853.415	2,782.797	2,805.627
2	1	2,427.037	2,384.060	2,397.220
2	2	1,712.534	1,707.360	1,712.096
2	3	1,744.141	1,742.610	1,746.540
2	4	955.684	947.780	948.215
2	5	2,061.024	2,084.370	2,092.536
2	6	2,746.064	2,660.590	2,679.474
3	1	2,421.748	2,401.520	2,415.164
3	2	1,364.752	1,362.280	1,365.666
3	3	2,160.889	2,153.250	2,161.870
3	4	907.029	917.090	917.530
3	5	2,119.986	2,173.339	2,184.021
3	6	2,513.877	2,457.440	2,472.357

Table 29. Functional Scenario Distances (km)

6.1.2.2.2 East Asian Scenario. This scenario, the first of three operational scenarios, was developed to test the performance capability of the conceptual BMD system in a scenario that encompassed a large waterspace area, large, simultaneous threat salvos, and several potential maximum effective range intercepts. Operational employment is a three-ship defense system providing defense of seven known targets from four known launch sites. The ships are strategically placed in locations to provide overlapping defense in relation to the launch and target sites. All targets in this scenario are land targets. BM launch sites, intended impact sites (targets), and ship position are shown in Figure 130 (launch site indicators, targets, and ship sizes are not to scale).

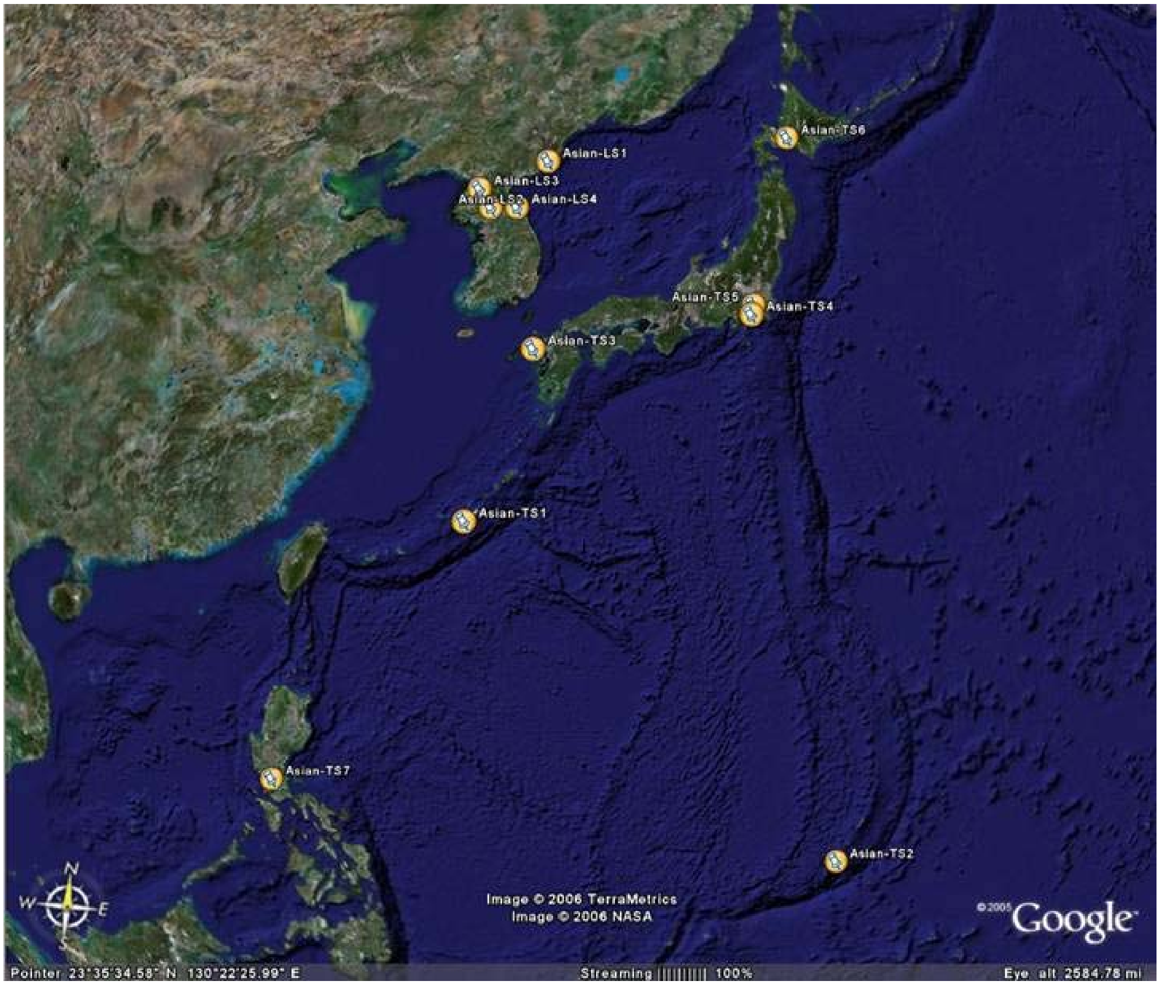

Figure 130. East Asian Scenario

In each salvo (model run) all launch sites can fire between 57 and 65 BMs (totaling 240-260 BMs in the air simultaneously) to specific targets. Each salvo is independent of one another and inventories of both BMs and interceptor rounds are replenished prior to start of each successive salvo. The number of BMs launched per launch site (between 57 and 65), and the ultimate targets of launched BMs are random to eliminate any learning curve of the system.

Table 30 indicates the distances between launch and target sites in kilometers. To improve accuracy for input into the threat model, distances were measured using an automatic grid position, a manual measurement grid position, and using Great Circle routes. Distances highlighted in red are designated as the shortest reaction time launcher and target combinations, and thus are the most difficult detect-to-engage sequences.

Launch Site	Target Site	Auto Grid	Manual Grid	Great Circle
1	1	1,611.742	1,690.990	1,611.035
1	2	3,475.494	3,451.970	3,405.054
1	3	849.619	937.210	849.447
1	4	1,135.681	1,177.310	1,108.834
1	5	1,116.763	1,157.410	1,090.879
1	6	1,056.145	1,078.160	1,071.448
1	7	3,028.255	3,052.050	3,007.245
2	1	1,360.600	1,360.880	1,362.233
2	2	3,374.904	3,280.050	3,318.491
2	3	657.942	660.960	660.545
2	4	1,225.276	1,212.680	1,213.105
2	5	1,216.998	1,205.660	1,206.048
2	6	1,332.569	1,356.360	1,357.062
2	7	2,732.730	2,686.892	2,711.900
3	1	1,444.208	1,447.106	1,447.603
3	2	3,475.570	3,382.450	3,420.985
3	3	756.184	760.930	760.536
3	4	1,310.217	1,295.760	1,296.461
3	5	1,300.114	1,286.680	1,287.339
3	6	1,366.793	1,385.257	1,385.787
3	7	2,795.313	2,753.660	2,774.782
4	1	1,375.289	1,373.650	1,375.062
4	2	3,328.402	3,233.140	3,266.544
4	3	636.832	641.259	637.387
4	4	1,125.625	1,118.683	1,110.571
4	5	1,115.613	1,110.138	1,101.952
4	6	1,223.411	1,256.272	1,250.100
4	7	2,777.406	2,726.177	2,756.448

Table 30. East Asian Scenario Distances (km)

6.1.2.2.3 Middle Eastern Scenario. This scenario, the most demanding of the three operational scenarios, was developed to test the performance capability of the conceptual BMD system in a scenario that encompassed a small water space area; large, simultaneous threat salvos; and several potential medium to smallest effective range intercepts. Operational employment is a three-ship defense system providing defense of eight known targets from six known launch sites. The ships are strategically placed in locations to provide overlapping defense in relation to the launch and target sites. All targets in this scenario are land targets. BM launch sites, intended impact sites (targets), and ship position are shown in Figure 131 (launch site indicators, targets, and ship sizes are not to scale).

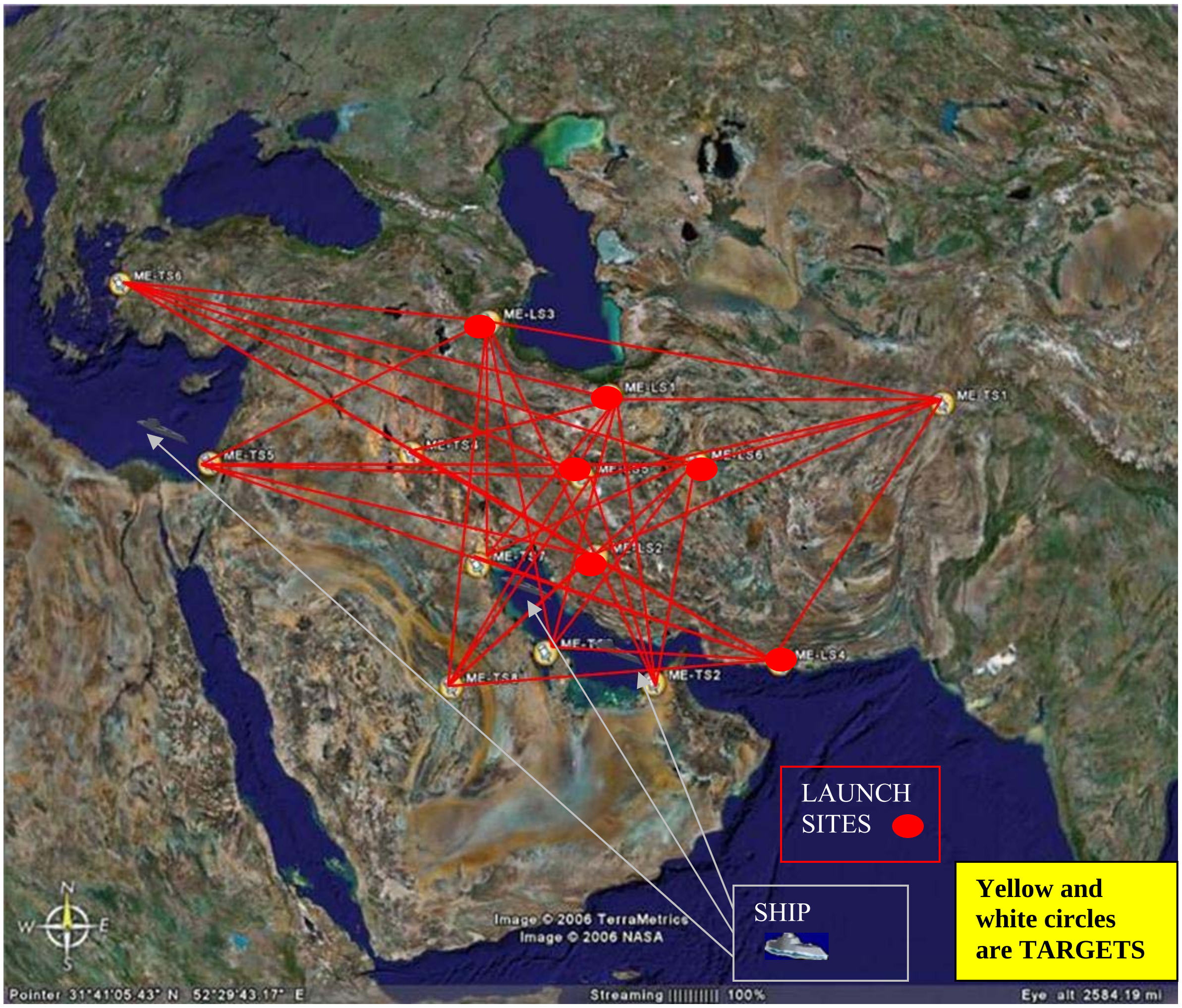

Figure 131. Middle Eastern Scenario

In each salvo (model run) all launch sites can fire approximately 40-50 BMs (totaling 240-300 BMs in the air simultaneously) to specific targets. Each salvo is independent of one another and inventories of both BMs and interceptor rounds are replenished prior to start of each successive salvo. The number of BMs launched per launch site (between 40 and 50), and ultimate targets of launched BMs are random to eliminate any learning curve of the system.

Table 31 indicates the distances between launch and target sites in kilometers. To improve accuracy for input into the threat model, distances were measured using an automatic grid position, a manual measurement grid position, and using Great Circle routes. Distances highlighted in red are designated as the shortest reaction time launcher and target combinations, and thus are the most difficult detect-to-engage sequences.

Launch Site	Target Site	Auto Grid	Manual Grid	Great Circle
1	1	1,451.547	1,578.468	1,442.516
1	2	1,203.500	1,211.261	1,202.395
1	3	1,093.840	1,049.571	1,091.083
1	4	866.853	727.920	857.023
1	5	1,793.452	1,634.848	1,759.823
1	6	2,304.953	2,218.898	2,338.155
1	7	892.602	789.904	882.472
1	8	1,390.988	1,296.666	1,376.429
2	1	1,601.480	1,635.130	1,638.151
2	2	583.448	583.160	582.990
2	3	454.574	458.185	452.556
2	4	860.336	881.999	876.670
2	5	1,705.401	1,725.200	1,729.044
2	6	2,422.570	2,518.980	2,533.057
2	7	488.765	489.185	489.100
2	8	827.366	816.893	818.047
3	1	1,983.822	1,965.348	1,960.237
3	2	1,629.029	1,637.840	1,640.933
3	3	1,373.551	1,381.400	1,382.876
3	4	649.764	630.770	630.346
3	5	1,435.413	1,386.278	1,364.919
3	6	1,791.073	1,803.986	1,788.087
3	7	1,001.983	998.814	1,000.540
3	8	1,526.691	1,515.887	1,519.725
4	1	1,264.747	1,325.200	1,326.556
4	2	534.887	539.260	539.120
4	3	979.246	982.140	982.540
4	4	1,765.458	1,771.530	1,775.918
4	5	2,561.466	2,583.640	2,599.715
4	6	3,321.397	3,407.858	3,432.290
4	7	1,326.463	1,319.915	1,329.084
4	8	1,372.958	1,374.433	1,379.641
5	1	1,577.122	1,597.338	1,592.571
5	2	903.408	903.172	903.285
5	3	741.584	739.457	739.327
5	4	714.491	719.305	719.007
5	5	1,633.788	1,626.536	1,629.482
5	6	2,261.837	2,329.951	2,340.534
5	7	569.161	556.153	561.757
5	8	1,043.613	1,023.463	1,030.452
6	1	1,105.882	1,127.565	1,122.327
6	2	922.732	926.750	927.109
6	3	994.214	997.654	997.915
6	4	1,180.276	1,181.687	1,182.249
6	5	2,104.779	2,095.242	2,097.504
6	6	2,704.112	2,755.248	2,759.466
6	7	993.896	985.912	992.900
6	8	1,383.381	1,370.503	1,378.815

Table 31. Middle Eastern Scenario Distances (km)

6.1.2.2.4 Sea Base Defense Scenario. This scenario, the last of three operational scenarios, was developed to test the performance capability of the conceptual BMD system in a scenario that placed the system in defense of an inbound Carrier Strike Group (CSG) or Expeditionary Strike Group (ESG). Operational employment is a single ship defense (in a picket position) system providing defense of an inbound strike group from a single, known launch site. The BM launch site, intended impact area and ship position are shown in Figure 132 (launch site indicators, targets and ship sizes are not to scale).

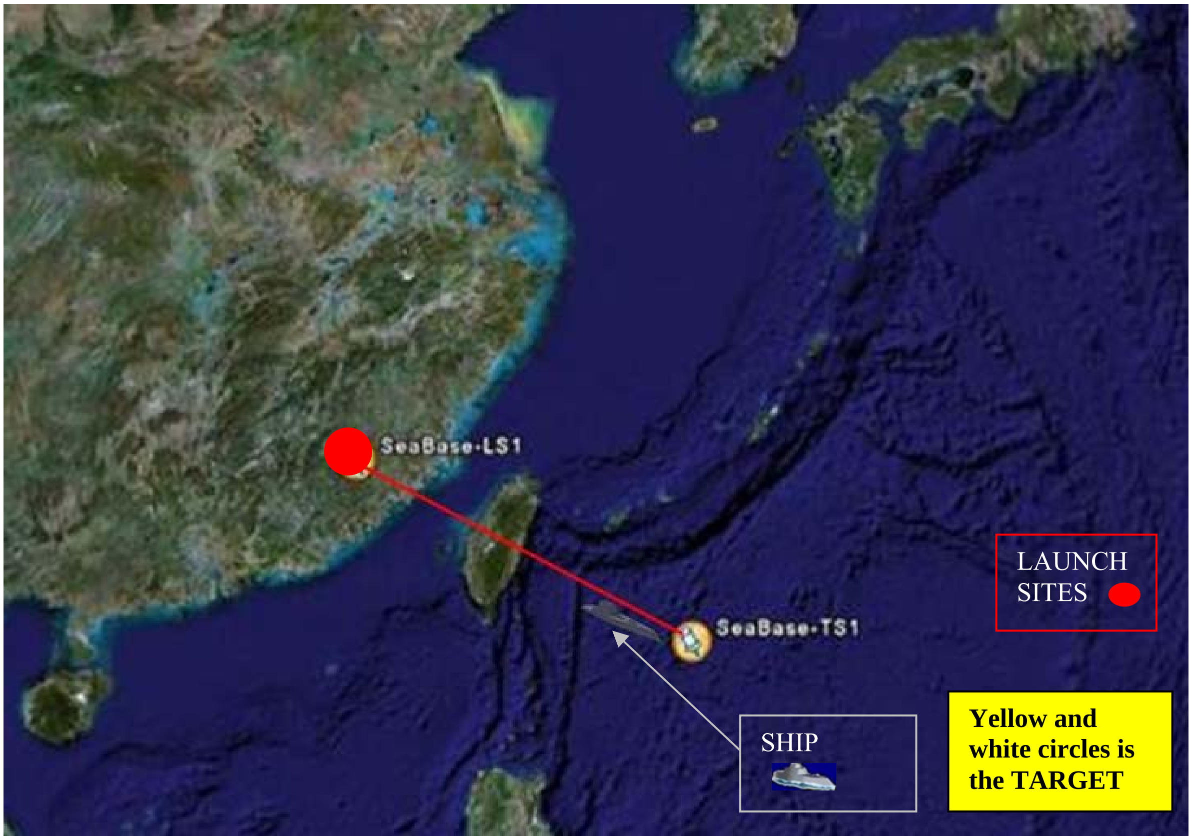

Figure 132. Sea Base Defense Scenario

In each salvo (model run) the launch site can fire approximately 30-50 BMs at the strike group target. Each salvo is independent of one another and inventories of both BMs and interceptor rounds are replenished prior to start of each successive salvo.

Table 32 indicates the distance between the launch and target sites in kilometers. To improve accuracy for input into the threat model, distances were measured using an automatic grid position, a manual measurement grid position, and using Great Circle routes.

Launch Site	Target Site	Auto Grid	Manual Grid	Great Circle
1	1	1,162.730	1,160.315	1,164.738

Table 32. Sea Base Defense Scenario Distances (km)

6.1.3 Final Modeling and Simulation Analysis Results

In the third and final iteration of simulation and analysis results, only the final design architecture's capabilities were tested in response to various geographical tactical scenarios. The previous simulative analysis determined which architecture performed the best among only the competing architectures. From the first two rounds of simulation and analysis, the 10 km/s railgun interceptor used in conjunction with the skin-of-the-ship assisted phased array radar was determined to perform the best against the technical performance measures. Therefore, this is the architecture being tested in this last iteration of simulation and analysis.

This final round of simulations determined how the most capable architecture from the previous two iterations of analysis performed in four different scenarios. The scenarios and simulations were devised to simulate and test the robustness and limits of the final architecture to a gambit of different situations and test the system's capabilities. These scenarios are unclassified approximations to the Major Combat Operations (MCO) scenarios used by the DoD for tactical and strategic planning. They were deemed Functional, East Asian, Middle Eastern, and Sea Base, and are geographically depicted in Figures 129-132. The positioning of the launch sites and targets in each of the scenarios created overhead, tail-chase, and head-on intercept situations to test the final architecture. This last iteration of the model also incorporated three sea-based platforms in the East Asian and Middle Eastern scenarios, as opposed to the single ship capabilities tested in the first two iterations of simulations. The introduction of three ships will serve to provide a more realistic operational battle group implementation to the scenarios. The Functional and Sea Base scenarios only simulated one ship. For the Functional scenario it was to assess the capabilities of a single ship system. It is called Functional because it is the baseline test of the final architecture and closely approximates the Stressed scenario used in the first and second iterations of modeling. The Sea Base only simulated one ship so that the vulnerability and the defensive capability of a single platform could be evaluated.

An additional change to the final round of modeling that had a significant affect on the analysis results is the reinstitution of the inorganic detection sensor network from the first iteration of modeling and analysis. This increased the probability of detection two fold from the second iteration modeling when only the organic radar sensors were utilized for threat missile detection.

The final iteration of simulations were conducted much like the first two rounds, but only run through 100 runs rather than 500 from iterations one and two. By the final round of simulations, the errors had been corrected in the model and the results were no longer yielding large variances. Therefore, fewer trials were needed to mitigate outliers in the data. Also, all of the competing architectures were eliminated which condensed many of the variables to the model.

Figures 133-140 show the results of the final iteration of simulative analysis. Each graph compares the four stressing scenarios to each of the eight metrics used to evaluate the architectures among one another as well as each of the architecture's mission success to a given set of conditions or scenarios. The metrics are the same metrics used to evaluate the architectures in the second iteration of analysis, and are listed in Table 33.

Probability of engagement given a detection	P(engage | detection)
Probability of detection	P(detect)
Probability of kill given an engagement	P(kill | engagement)
Probability of false alarm	P(false alarm)
Probability of hand-off given a detection	P(handoff | detection)
Time from detection to BDA	T(detect→BDA)
Time left to reengage after first cycle	T(reengage)

Table 33. Architecture Measures of Performance

The probability of detection, P(detect) in Figure 133, determines the proportion of threat missiles detected by either organic (SOTS + PAS radars) or nonorganic (satellite) assets. In the second iteration of simulations, the nonorganic assets were removed from the simulations to obtain a more accurate assessment of the radar architectures' performances. In this final iteration of simulations, the nonorganic assets were reinstituted to simulate a realistic, network-centric, future battlefield. The conformal plus phased array radars performed very well in all four scenarios. The radars performed perfectly in the functional scenarios and virtually the same in the other three. With respect to the Asian, Middle Eastern, and Sea Base scenarios, they did not report 100% detection because of minimum detection range and height constraints of the threat missile and random error. First, a threat missile cannot be detected below a certain height or beyond a certain range. These specifications are summarized in Section 6.1.3 of this report. Secondly, in order to simulate a more realistic operational situation, the model was set to induce a rare, random error that would cause the detection assets to not detect an airborne threat missile. Due to the random nature of this error, it did not occur in the Functional scenario at all, but it did in the other three scenarios.

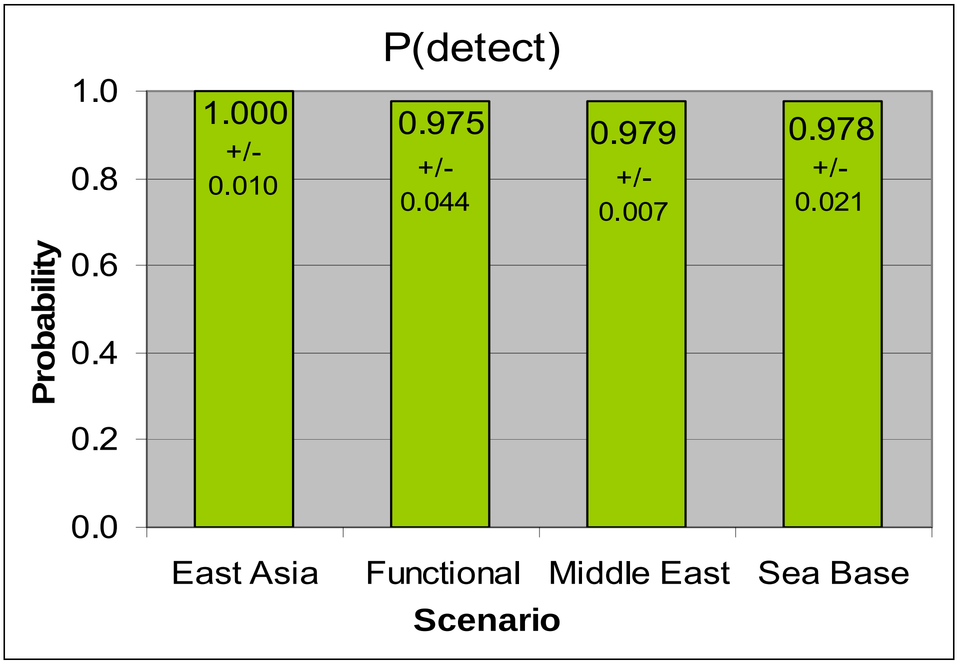

Figure 133. P(detect)

Probability of engagement, P(engage) in Figure 134, evaluates what percentage of the threat missiles the architecture is able to positively identify and fire at. This does not address whether the engagement was successful or failed; that is addressed in another metric. The Functional and Sea Base scenarios were responded to with 100% engagement. The distance from the ship to the threat missile is never greater than the railgun's maximum engagement range, and is therefore able to engage it every time in the Functional scenario. In the Sea Base scenario, the threat missiles were always headed directly for the ship, so they came within range of the ship with enough time to engage it.

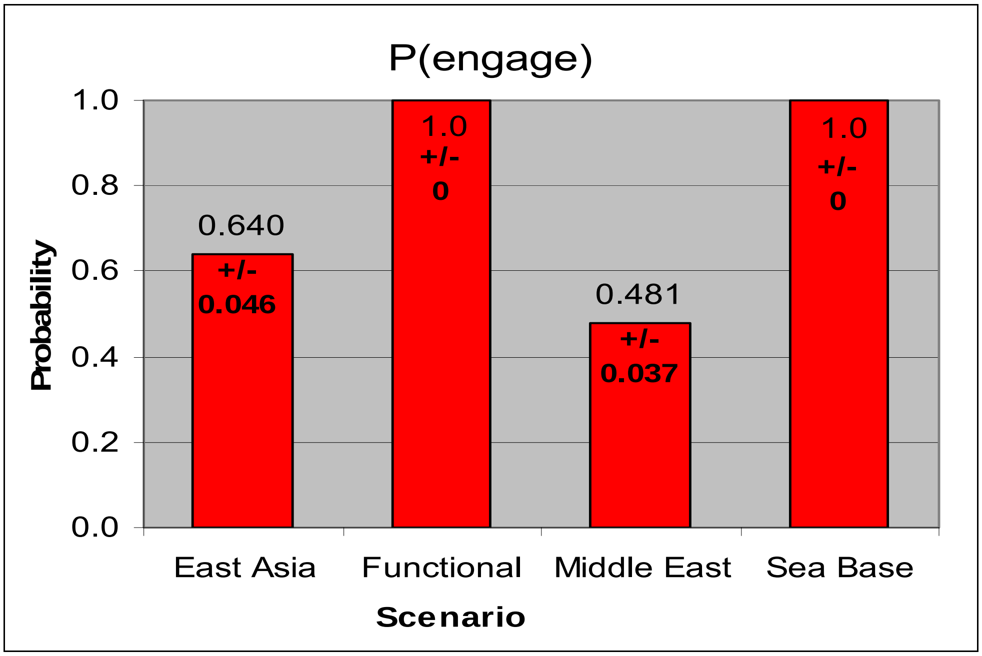

Figure 134. P(engage)

The Middle Eastern and Asian scenarios resulted in a lower performance of engagement. This is due almost exclusively to the sheer number of airborne threat missiles. The Asian scenario simulated anywhere from 230 to 260 airborne threat missiles and the Middle Eastern scenario simulated anywhere from 250 to 300. The system saturated at approximately 150 airborne threat missiles. Therefore, anything more than that and the system would not be able to engage it.

Probability of kill given an engagement, P(kill | engagement) in Figure 135, assesses the proportion of threat missiles destroyed by the railgun interceptor that are also detected and engaged. The graph shows that the results among scenarios are virtually the same. Since it is impossible to know the achievable probability of kill for a conceptual system without building and live fire testing it, a requirement of 90% probability of kill given an engagement was programmed into the model. Although 90% is high when compared to analogous weapon systems, it is feasible due to the devastation that would ensue should it fail. This metric, therefore, gives a feasible, yet conservative, performance to the model and simulation results. The graph thus verifies that the system performed to specification and further helps to verify the correct operation of the model.

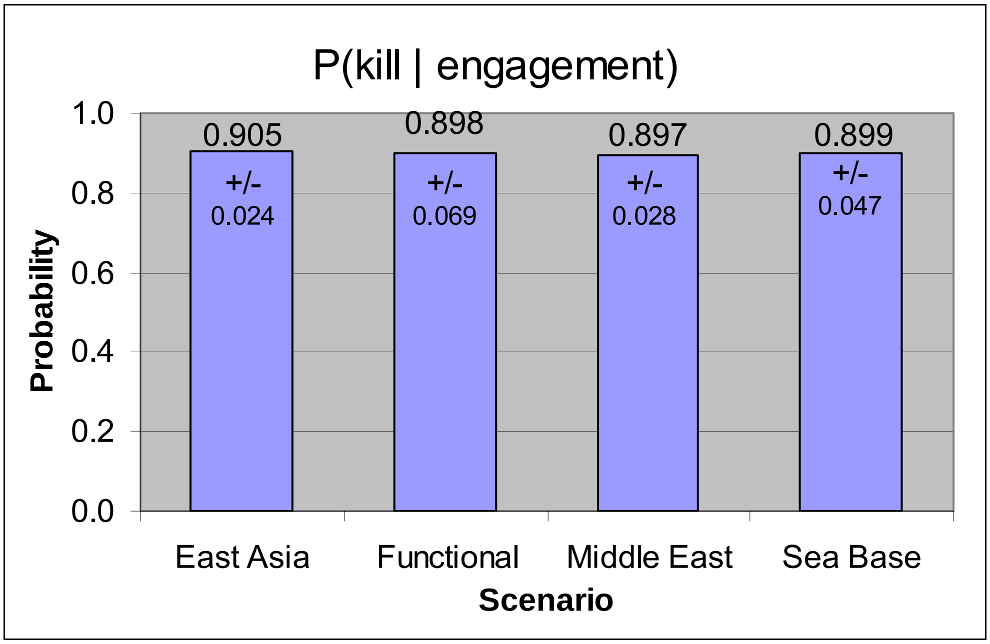

Figure 135. P(kill | engagement)

Probability of handoff given a detection, P(handoff | detection) in Figure 136, assesses the system's inability to successfully engage and destroy the target. A handoff is the passing of intercept responsibility to a more capable asset if the sea-based platform is unable to engage or destroy the threat missile by the end of threat missile midcourse. A handoff can only occur if there is an initial detection; otherwise, the system does not know the threat missile is actually airborne. In the Functional and Sea Base scenarios, the handoff rate was very low because no threat missiles were ever out of range of the ship's detectable or lethal range and there were few threat missiles compared to the Asian and Middle Eastern scenarios—70 to 100 threat missiles in the Functional scenario and 30 to 50 in the Sea Base scenario. However, in the Asian and Middle Eastern scenarios, the rate of handoff is much greater because of the high volume of airborne threat missiles, which is due to saturation as addressed in the probability of engagement section.

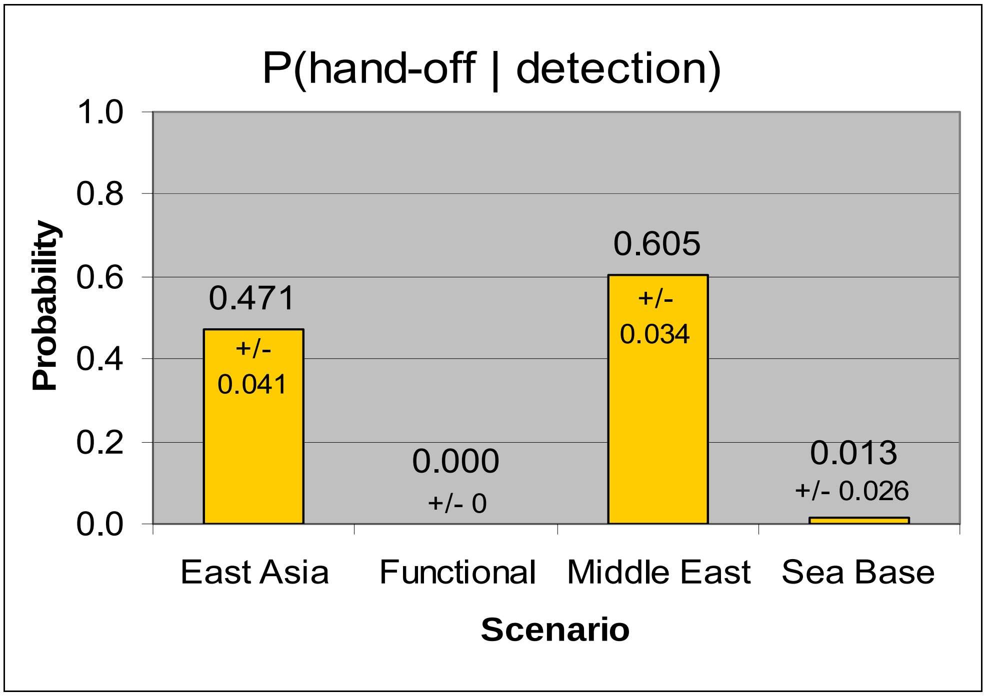

Figure 136. P(handoff | detection)

Handoffs are not system failures, however. If the threat missile can be handed off, it has at least been detected and is therefore known about. If the ship is unable to engage or neutralize the missile, the intercept responsibility can be passed on to a more capable intercept asset. This way, the threat missile remains queued in the missile defense network and maintains the chance of being intercepted. This makes it a very worthy platform in the network of missile defense assets. Figure 136 also shows the effects of system saturation in the Asian and Middle Eastern scenarios. Once the sea-based assets continued to detect, but could no longer engage airborne targets due to weapon firing rate limitations, the system would hand them off to the Automated Battle Management System to be reallocated to an asset with a higher probability of kill.

Probability of false alarm, P(false alarm) in Figure 137, is the metric that evaluates how many threat missile detections are made when there is no threat missile present. Like P (kill | engagement) discussed above, with only a conceptual system there is no real way of determining the achievable probability of false alarm. As shown in the graph, all four scenarios depict close to the same results for false alarm rate. This is due to the fact that it was a predetermined metric in the model. It serves to induce realistic, operational error into the system and allow for a more conservative performance of the system. In the model, probability of false alarm is 0.02 with a standard deviation of 1.

This is a relatively high standard deviation, but it is feasible due to the multitude of internal and external variables that can contribute to a false alarm. Adverse weather conditions, atmospheric effects, different threat missile characteristic, and contacts with similar radar return characteristics to a threat missile can induce a false alarm.

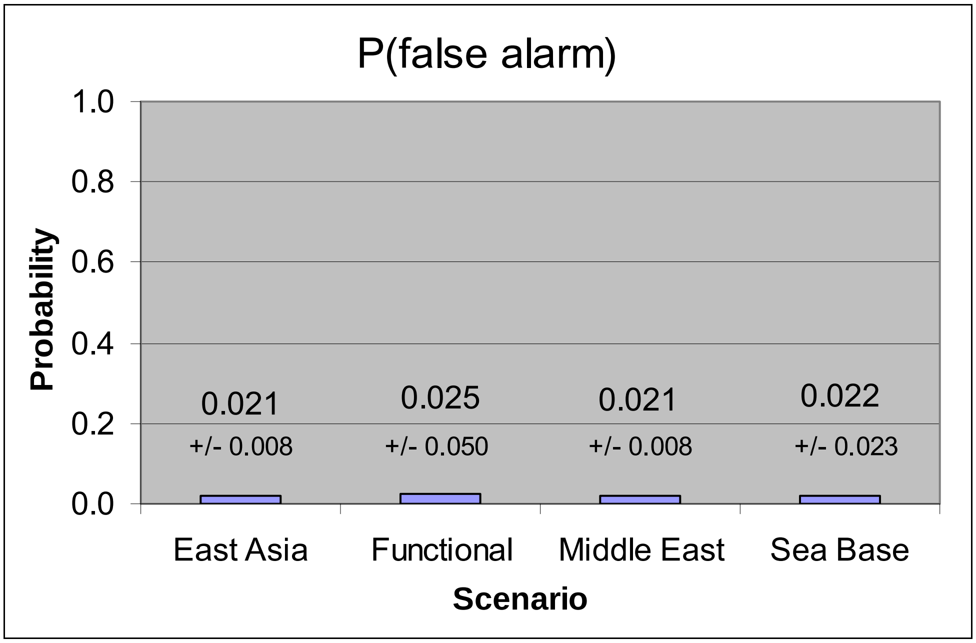

Figure 137. P(false alarm)

Recording this metric allowed for verification of the model's output. It was derived from current analogous radars systems and from Dr. David Jenn's technical input for the conformal SOTSR.[80]

The Mean Time Available for Reengagement (Figure 138) depicts the time the system has left to engage the threat missile should it fail to destroy it during the first engagement. It is determined by subtracting the time for the system to initially detect the threat missile, engage it, and conduct BDA on it from the total flight time of the ballistic threat missile through end of midcourse. Depending on the threat missiles' location in relation to the ship and the radar's ability to maintain a lock on the threat missile, this amount of time may be enough to reengage or it may not be. If it is not enough time to reengage the threat missile, the Automated Battle Management System will hand engagement responsibility off to a more capable intercept platform. The Functional scenario had a much higher available time to reengage because the sea-based assets were

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[80] David Jenn, "Wirelessly Networked Opportunistic Digital Array Radar," Mechanical Engineering Department, Naval Postgraduate School, Monterey, CA, 2005, p. 1-37.

positioned in such a way that when the threat missile broke its minimum detectable height it was near the closest point of approach to the ship, thereby lessening the actual engagement time of the railgun interceptor and leaving a large amount of time to reengage.

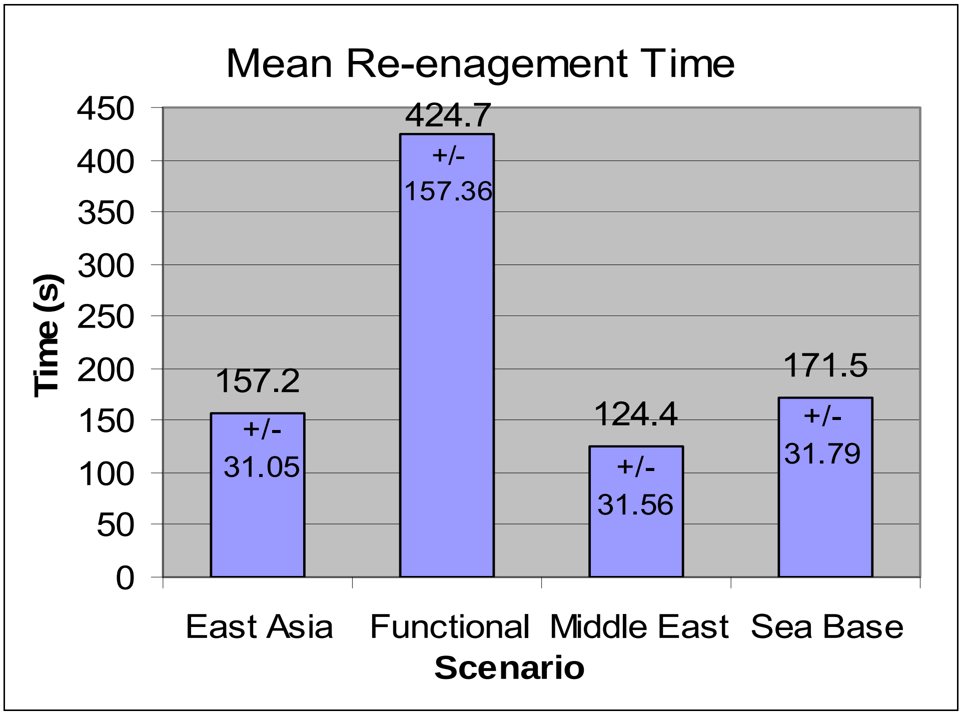

Figure 138. Mean Reengagement Time

The Sea Base scenario exhibited a lesser reengagement time because the threat missile was always headed directly for the ship and therefore lessened the time of flight of the BM as well as its window of engagement. The Asian and Middle Eastern scenarios are even lower due to the vast number of launch sites and targets, as seen in the geographical scenario diagrams in Figures 130 and 131. Since the metric is recorded as a mean, there are some threat missiles that have much longer flight time than others and therefore averages out to the results in the above mean reengage time graph.

Mean Time until the End of Ballistic Missile Midcourse (Figure 139) measures the time from the threat missile launch until it reaches the end of midcourse. It addresses the total window that the threat missile can be engaged by the sea-based asset. Any engagement after the end of midcourse will have to be handed off to another engagement asset capable of terminal flight engagement. This metric is also analogous to threat missile launch range. The Sea Base scenario has only one launch site and one target. It simulated the shortest threat missile flight path and therefore has the shortest flight time. The Asian, Functional, and Middle Eastern scenarios have a multitude of launch sites firing at several targets at varying ranges. This metric is also an average of all of the threat missiles launched within each scenario. This metric is the basis in determining time left to reengage and optimal ship placement.

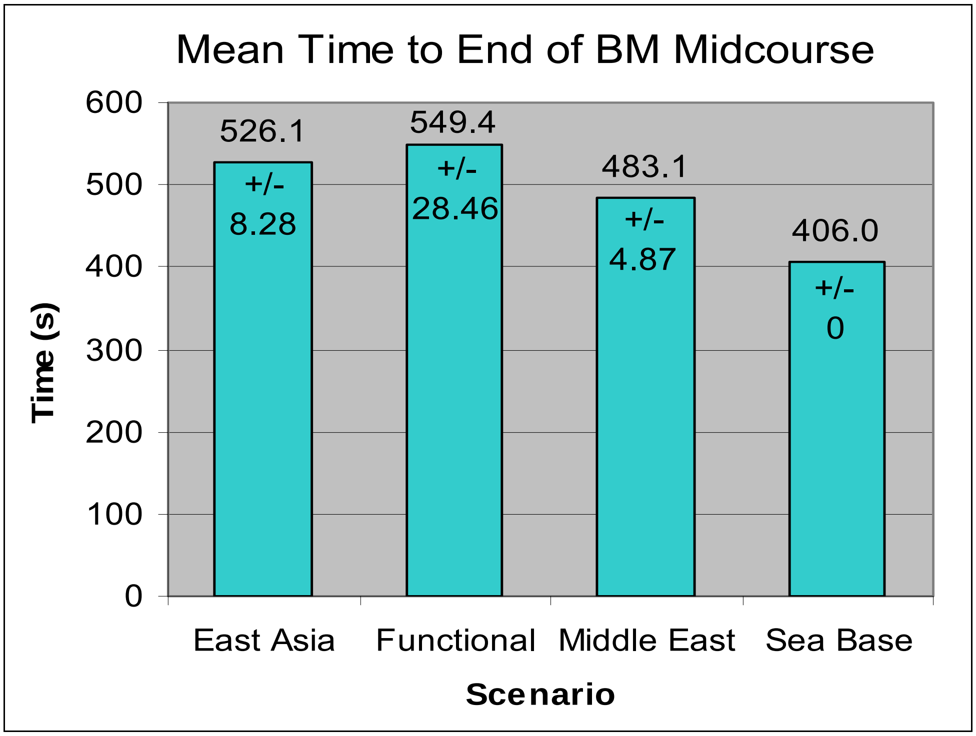

Figure 139. Mean Time to End of BM Midcourse

Mean time for the missile defense system to detect, engage, and conduct BDA on the threat missile is recorded in the graph in Figure 140. The results of this are highly dependent on the position of the ship and the flight path of the threat missile. This is reflected in the varying results in each of the scenarios. In the case of the Sea Base scenario, since the threat missile was fired directly at the ship, the engagement cycle was very short. The Functional scenario also exhibited a short engagement cycle time because of the ships' placement in the battle space. Once the threat missiles were detected, they were near the closest point of approach to the ships and therefore yielded a short engagement cycle time. The Asian and Middle Eastern scenarios produced longer engagement cycle times because many of the engagements were tail-chase situations and therefore took longer and increased the average of the recorded metrics.

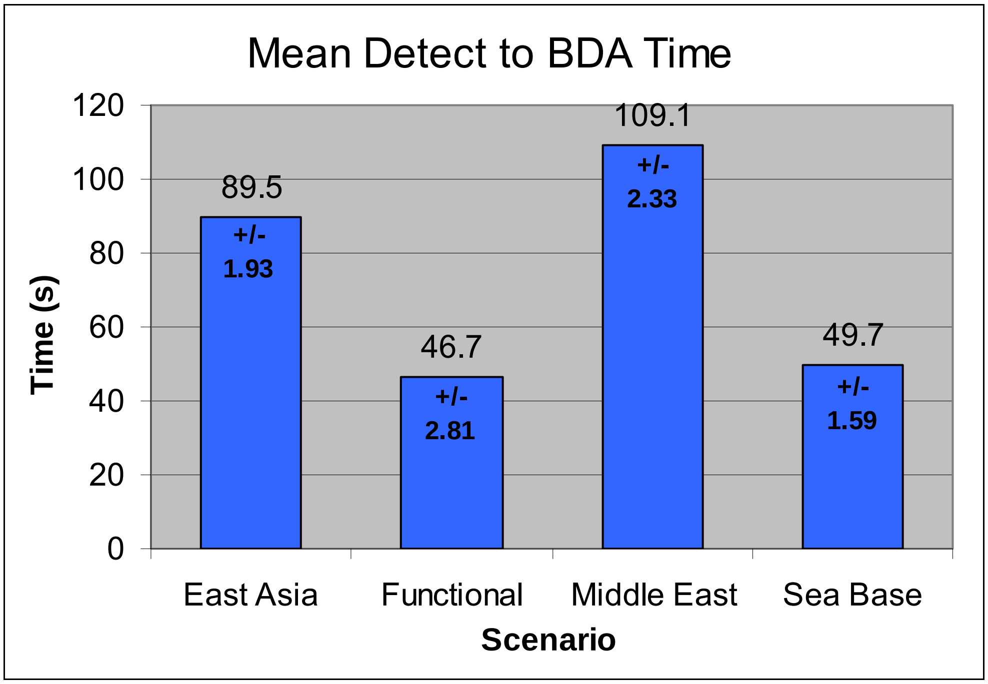

Figure 140. Mean Detect to BDA Time

The analysis concludes that the final architecture of the 10 km/s railgun weapon with the skin-of-the-ship assisted phased array radar is a very valuable and formidable asset to the layered missile defense network. It performed excellently in the Functional and Sea Base scenarios, handing off only 1% in the Sea Base scenario, engaging 100% of the threat missiles, and maintaining a 90% kill ratio. The Asian and Middle Eastern scenarios also performed well. Though the handoff ratio was between 40% and 60%, the salvo of threat missiles was unrealistically high, topping out at 300 airborne threat missiles. The usefulness of these scenarios was to determine when the system would saturate and more assets would be needed. From the predetermined metrics and scenario variables, the system saturated at approximately 150 airborne targets. Even though the system was unable to engage any threat missiles after that, it still served as a detection and tracking asset to other capable intercept platforms.

6.2 CONCEPT OF OPERATIONS (CONOPS)

6.2.1 Overview

A weapon or weapon system is defined in the context of the tactics, techniques, and procedures that govern its employment. In the field of sea-based BMD, CONOPS development is a unique challenge, in that this is a very new and still developing form of warfare.

The CONOPs proposed by the SABR team are a derivative of existing anti-air warfare (AAW) tactics employed by Naval units. Vessels equipped with the SABR system are looked at as long-range picket vessels, whose mission is to detect, track, and intercept a target at the earliest possible point, as far from friendly forces, or friendly territory, as possible. With this in mind, the SABR team proposes a deployment construct similar to that currently used by the Navy's Strategic Deterrent Submarine Force. American BM submarines (SSBNs) deploy as single, self-sufficient units, and operate autonomously within large areas of open ocean. If necessary, these submarines can launch their weapons and return to the cover of depth with little concern for counterattack.

While a surface vessel can never hope to have the same advantages of stealth that are inherent to a submarine, the concept of a vessel able to deploy and operate as a self-sufficient unit for several months at a time are ideal for the SABR concept. SABR vessels would be able to operate away from the Strike Group and Sea Base for extended periods of time, positioning themselves in an optimum location to counter the expected BM threat.

Where possible, the SABR group proposes a deployment of up to three BMD-capable surface assets to a theater of potentially hostile BM action. These vessels are linked electronically to each other and to nonorganic sensor systems. With this sea-based defense perimeter established, these vessels will be capable of early detection and engagement of enemy missiles. The precise stationing of assets is based on calculations involving a variety of factors.

6.2.2 CONOPS Validation

6.2.2.1 Ship Placement

The locations of intercepting assets have a crucial effect on their performance. Thus, optimizing ship placement will contribute to the success of the interception mission. The Brown et al. JOINT DEFENDER model[81] serves as a basic reference for how to optimize ship placement. A brief, intuitive explanation of their approach is presented here.

For each possible BM attack launched from specific site to specific target, there is an optimal position that will maximize the probability of success for interception. For example, examine a worst case in which the asset is located too far, and the attacking BMs are out of range. Range affects many parameters: the probability of detection, the probability of hit, the time to target, and thus, the number of shoot-look-shoot salvos and the number of simultaneous interceptions (Table 34).

Affected Factors / **Placement Issue**	**Probability of Detection**	**Probability of Hit**	**Number of Salvos**	**Number of Simultaneous Interceptions**
Range to Target	X	X	X	X
Angle to Trajectory	X	X		
Medium Between Ship and Target	X			

Table 34. Performance Factors Affected by Ship Placement

For each possible asset placement program, there is a performance measure (such as expected number of leaking missiles or probability of leak) for each of the possible attacks. The placement itself cannot ignore other operational considerations such as force security and logistics, thus the positioning of the assets is limited to specific areas. As the enemy attack plan is unknown, the planner should take into account many possible scenarios and decide how to weigh them.

Another issue is the role of enemy intelligence and the enemy's capability to reprogram their attack, such that SABR ship location is taken into account.

Taking all these factors into account allows optimization of the ship placement for the predicted scenarios, as shown in Brown. The factors taken into account by JOINT DEFENDER are:

- System performance as function of placement scheme in terms of probability of negation (other MOEs can be used instead). This performance may be calculated or evaluated by engineering tools or simulations, which take into account all performance parameters, such as

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[81] Brown et al., "A Two Sided Optimization for Theater Ballistic Missile Defense," *Operations Research*, Vol. 53, No. 5, 2005, pp. 745-763.

probability of detection, probability of hit, probability of kill, etc., of a specific placement in a specific scenario.

- Operational limitation on the possible placement coordinates.
- Importance or likelihood of specific scenarios.
- Enemy ability to reprogram their attack due to intelligence about defender's defense scheme (two-sided optimization).

6.2.2.1 Heuristics for Ship Placement

6.2.2.1.1 Introduction. Unfortunately, the reference optimization method requires a lot of input data, which is currently unavailable, and will not be always available for the planner. A set of heuristics that will yield good ship placement is used instead. The following set of assumption is required:

- The attacks are identical in terms of likelihood, number of missiles, and importance of interception.
- The damage of each attack is cumulative, i.e., the damage from three missiles hitting the same target is the same as the damage done by three missiles hitting three different targets. Furthermore, this attribute holds even for large number (tens) of missiles. This assumption doesn't hold if the attacking missiles are relatively accurate and if spreading the attack induces larger difficulties on the defender (to rescue, evacuate, and recover).

In this case, the ship placement problem reduces to a geometrical placement, in which the placement should optimize an objective function. This objective function depends on the mission and the number of missiles that are expected to be launched from each site. An *attack scheme* is defined to be the pair of a launch site and a target. If each attack scheme is likely to involve large numbers of attacking missiles, such that the system is unlikely to engage all of the attacking missiles even once, the objective function is to maximize the total number of interception salvos, which will maximize the number of rounds the ship can fire in order to intercept the missiles, and thus minimize the expected number of leaking missiles. If the attack is small relative to the intercepting force, then the chances are that the force will engage all the detected missiles of each attack scheme, and thus the placement should maximize the number of attack schemes covered by the force.

The large attack assumption holds if the force means are scarce, relative to the attacker's potential arsenal. A small attack can be assumed if there will be as many interceptors as needed relative to the possible attack.

6.2.2.1.2 Heuristics. For each scenario, potential placement patterns will be located by operational officers, taking into account operational constraints such as logistics and security. Assume a cookie-cutter capability for the interceptors: as long as the interception is within range, the probability of kill and detection probabilities are constant. The range of the interception is not symmetrical around the ship due to the motion of the BM. Nevertheless, for simplicity assume a circular effective range.

For large attacks, ship placement should maximize number of salvos, thus should maximize the length of trajectories within the interception range, while minimizing distance to the trajectories. These two opposing trends will induce an optimal position. The number of salvos is proportional to one over the average distance to each trajectory, and proportional to the length of trajectory within range. As long as the attack is still large (i.e., there are more BMs than BMs that can be intercepted), the force should be concentrated to cover the densest area of the scenario in terms of trajectory length, for example, in the Asian scenario as seen in Figure 141.

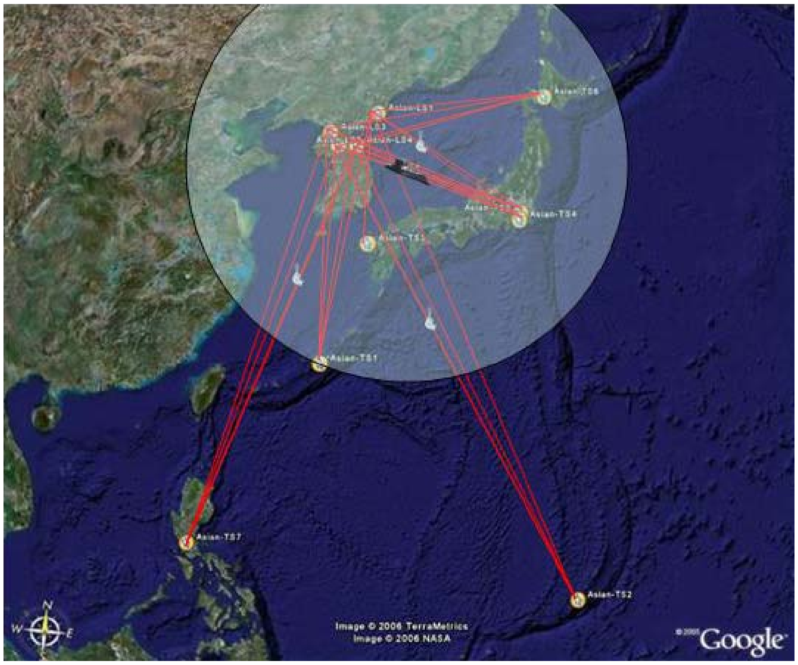

Figure 141. Best Force Placement for Large Attack in Asian Scenario

For small attacks (Figure 142) the number of trajectories in range should be maximized. Additional force components should be placed in new positions, such as additional trajectories that will be covered. In the case of the Asian scenario, all the trajectories are covered in the large attack scenario, yet a more balanced placement will yield a bit better results for the long trajectories, while reducing the overhead in the short trajectories.

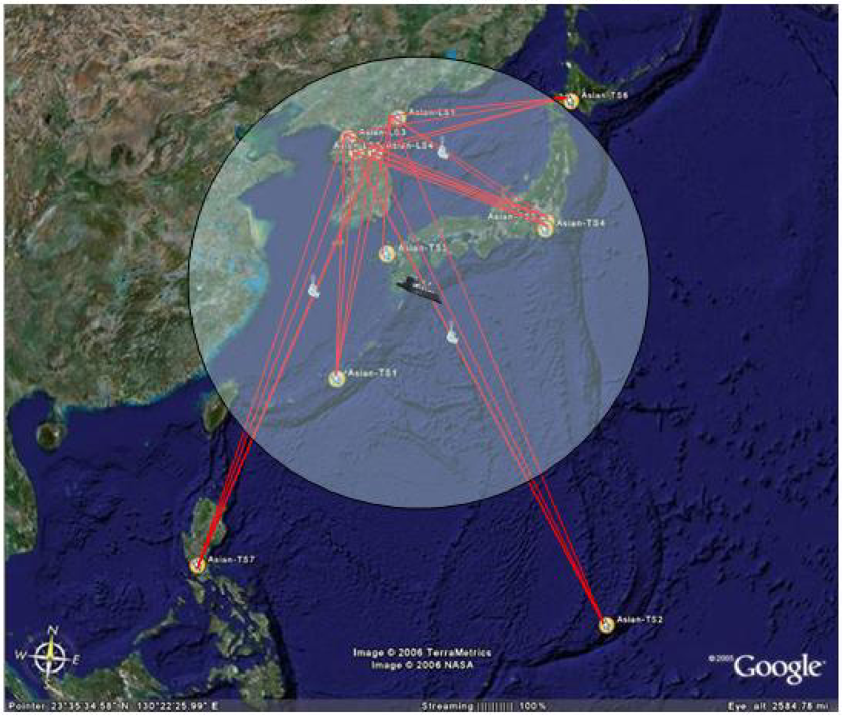

Figure 142. Best Force Placement for Small Attack in Asian Scenario

If the size of the attack is unknown, the large attack placement is more robust as it has clear advantage on the placement suggested for the small attack in the case of large attack.

6.2.2.2 Number of Ships

The number of available interception assets has an influence on the force deployment. The number of ships needed can be extracted from the number of salvos needed to achieve an improvement in overall interception performance.

For the high Single Shot Kill Probability (SSKP) attained by the SABR system, a single salvo per BM will yield very good results—on average, over 90% of the intercepted BMs will be intercepted. More than two salvos will not improve the interception success significantly, as it becomes almost 100%.

Using the simulation results regarding the operational scenarios, the average length of an interception salvo was 64 seconds for the Asian scenario and 80 seconds for the Middle-Eastern scenario. The average duration of interception window was 530 seconds for the Asian scenario and 500 seconds for the Middle Eastern scenario. This is an average of 6-8 salvos by each ship. The duration of each engagement is assumed to be 3 seconds, resulting in an average of more than 20 simultaneous engagements by each ship during the time of 64 seconds. The result is that each ship can produce more than 120 engagements during an attack.

If there are two salvos per BM in an attack, each ship can intercept 60 BMs. An attack will be small if it involves less than 60 BMs per ship in the defending force. It will be large if it involves more than 120 BMs per ship in the defending force. The cases between these two are intermediate cases, in which the heuristics for ship placement are too rough to yield a good result, and more detailed optimization is then needed. For example, assume that in the Asian scenario, 10 BMs can be fired in each attack scheme simultaneously. If the hypothesis is that the attack is *large*, the force (single ship) is placed, as shown in Figure 141. There are 25 attack schemes with 250 BMs covered by the ship. In this case, the attack will remain *large* even if the force includes two SABR systems. The attack will be considered *small* for a force of more than four ships.

When the attack is small, the force will intercept almost any detected BM, thus the performance is limited by the detection system. When the attack is large, the force will intercept as many as it can, yet a significant number of missiles is likely to leak through the defense.

6.3 SENSITIVITY OF FINAL ARCHITECTURE TO REQUIREMENTS

6.3.1 Requirements Satisfaction

With a preferred final architecture developed it is important to understand not only that the BMD system meets all of the requirements of the SABR project, but if the requirements are constraining or can be related with respect to requirements. The requirements are:

- Rapidly deployable sea-based platform capable of prolonged operations.
- Stable platform capable of operations in heavy seas.
- Detect and track over the horizon BM launch and flight path.
- Share real-time sensor, weapon, fire control, and BDA data among coalition forces.

- Prioritize threats and optimally pair assets with highest probability of kill.
- Designate targets with a low probability of kill to other assets.

These requirements were used to develop the MOEs and MOPs of the system, and also aided in the identification of the solution-neutral, top-level functions that were developed.

When developing the preferred architecture, all of the requirements and top-level functions had to be kept in mind. Going through each of the requirements, the SABR team was able to verify that each requirement was meet in some way by the conceptualized BMD system. Looking at requirements 1 and 2, the SABR project BMD system was developed to be placed on a sea-based platform, such as current ships. These two requirements have been provided to a group of TSSE students to develop a platform capable of effectively employing the BMD system in a future project. As for the third requirement, modeling showed that by incorporating a SOTSR with a MFPAR, early warning range could be extended to ~2,000 km and detection range could be increased ~1,000 km, thus fulfilling requirement 3.

The bounding assumptions of the project stated that an automated battle management system exists on the sea based platform being used for BMD and that a CIX exists between all actors in the global IBMD System. These two assumptions were crucial to the team being able to meet requirements 4, 5, and 6. Using these bounding assumptions, the modeling group of the SABR team was able to create a model containing various parameters to incorporate the C2 process and communication exchange of the system. All of the models were created using a three-ship force structure. This allowed the team to analyze the interactions between the ships and the time delays involved. This conceptualized system utilizes the sharing of all data from BM detection through BDA via the CIX. Using this data-sharing capability, the ABMS can prioritize threats and pair the asset with the highest probability of kill to the threat, thus fulfilling the remainder of the requirements needed for the SABR project.

6.4 COST ANALYSIS OF 2025-2030 SABR ARCHITECTURE

The following are rough cost estimates for the proposed architecture components, based on current data and source contacts. Note that the directed energy option and phased array radar were not included due to previous elimination from simulation results. The SM-3 missiles are launched via a standard MK-41 VLS, already outfitted on AEGIS surface ships. Also, included in the platform cost (CG(X) design, Table 36, is the SPY-1B phased array radar, which will be used in conjunction with the SOTSR. The estimate for the cost of a 20-kg, guided, railgun projectile was increased two-fold from the lower end, due to the price of miniaturization of guidance technology and other factors. The power supply for the railgun interceptor was not estimated for cost due to the anticipated electric drive capability of U.S. Naval ships by the year 2025. Estimates have shown that 94 2-kg, railgun salvos (four rounds) can be fired for the cost of one SM-3 missile salvo (two missiles). Total system cost (with one year of operations with 10 salvos; FY$2025) for an SM-3 interceptor-equipped platform is estimated to be $5.77 billion. Total system cost (with one year of operations with 10 salvos; FY$2025) for a railgun interceptor-equipped platform is estimated to be $5.64 billion, for a savings of approximately $126 million (Table 35).

	SM-3	**Railgun**
Platform	$3,439,360,000	$3,439,360,000
Railgun	$0	$140,000,000
10 Salvos	$226,000,000	$2,400,000
1 Year of Operations	$29,019,600	$29,019,600
SOTSR	$130,858,950	$130,858,950
Total (FY$2006)	$3,825,238,550	$3,741,638,550
Inflation Index	1.5076	1.5076
TOTAL (FY$2025)	**$5,766,929,638**	**$5,640,894,278**

Table 35. Total System Cost Comparison with One Year of Operations (Base Year 2006).

Phase	**Estimated Cost ($Billion, FY2003)**	**Primary Basis of Estimate**
Detail Design	0.5	DD(X) estimate
Basic Construction	0.8	Adjusted DD(X) estimate
Electronics	0.6	Adjusted DD(X) estimate
Hull, Mechanical, and Electrical Systems	0.1	DD(X) estimate
Ordnance	0.6	Adjusted DD(X) estimate
Other	0.2	DD(X) estimate
Subtotal	2.3	
Change Orders	0.4	Percentage of production costs
Total Production Cost	2.7	
TOTAL CG(X) COST	**3.2**	

Table 36. Estimated Costs for CG(X) Production.[82]

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[82] Congressional Budget Office, "Transforming the Navy's Surface Combatant Force," Appendix: Cost Estimates for New Ships in the Navy's 160-Ship Plan and CBO's Option I, 2003.

6.4.1 Missile Interceptor (SM-3)

Cost per missile: $11.3 million (Block 1)[83]

6.4.2 Railgun Interceptor

Cost per mount: $65-$75 million[84]

Cost per guided projectile: $30,000-$45,000 (20-kg round)[85]

Cost per 2-kg guided projectile: $60,000 (assuming increased miniaturization costs for technology)

6.4.3 Skin of the Ship Radar (SOTSR)

Based on a 7 April 2006 interview with Dr. David Jenn, Department of Electrical Engineering, Naval Postgraduate School, Monterey, California, the following is an estimate of individual components for the SOTSR system. The total is tallied in Table 37.

- Individual Arrays:
  Circuit board – $200
  Radar element – $500
  Total cost – $700
- TR Module:
  Modulator – $100
  Demodulator – $100
  DDS – $100
  Wireless interface – $100
  LNA – $500
  Power amplifier – $5,000
  Controller – $2,000
  Sync circuit – $1,000
  Beamformer and controller – $10,000

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[83] "The NTW Block 1 program was officially projected to cost $5.7 billion for just 80 SM-3 missiles (at $11.3 million per missile) on 4 ships" – Director, Operational Test and Evaluation, *Annual Report, FY 2000*, Washington, D.C.: United States Department of Defense, February 2001, p. V1-19.

[84] Data received from George M. Bates, Northrop Grumman Corporation, on 18 May 2006.

[85] Data received from George M. Bates, Northrop Grumman Corporation, on 14 April 2006.

Small antenna – $50

- Subtotal – $20,350

	Individual Cost	Quantity	Subtotal
Array	$700	1,200	$840,000
TR Module	$20,350	1	$20,350
Design Costs[86]	$50,000,000	1	$50,000,000
Integration and Fabrication[87]	$80,000,000	1	$80,000,000
TOTAL			**$130,860,350**

Table 37. SOTSR Costs

6.5 SENSITIVITY ANALYSIS

The characteristics given to any interceptor are crucial to a system's overall performance and employability. Whether it is the interceptor's fly-out velocity or its overall ability to kill the target, they both contribute heavily to the system, but they are not the only factors affecting the system's overall performance. One of the primary factors is the system's ability to track the BM threat. The tracking capability of the system sets the upper limit of a system's overall performance, regardless of the interceptor's velocity or probability of single shot kill. It simply will not allow the system's overall performance to exceed the ability to track the target. An interceptor's ability to kill a target, how fast it can engage the target, and the salvo size to be fired are of primary concern when performing a trade-off analysis. Each of these factors, either by themselves or in conjunction with any other factor, can bring significant improvements to the interceptor's contribution to the system's overall performance and must be balanced accordingly and planned in coordination with improvements to system tracking capabilities.

6.5.1 Range Benefits of Increased Interceptor Velocities

For any interceptor to be effective it must be able to attain a sufficient velocity to consummate an engagement within the desired range and altitude envelope. This basic philosophy was used to compare the four modeled velocities plus an additional velocity, which was determined post modeling as necessary to accurately achieve the specified

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[86] Estimated from current analogous systems.

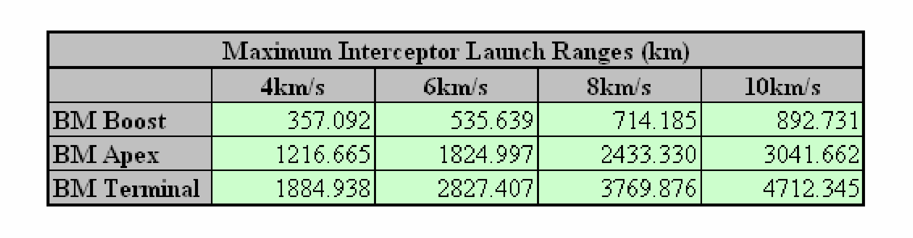
[87] Estimated from current analogous systems.

4,400 km maximum effective range of the interceptor. The increase from 10.0 km/sec to 10.6 km/sec provided little increase in the ship's maximum allowable operating area and was subsequently not modeled.

The ranges used in simulation were selected based on current capability and an estimated projection of future capability. The SM-3 block 1 currently in flight test by the United States Navy is an interceptor missile with a near 4-km/sec velocity. The block 1's subsequent replacement, the SM-3 block 2, is expected to have a velocity approaching 6 km/sec.[88]

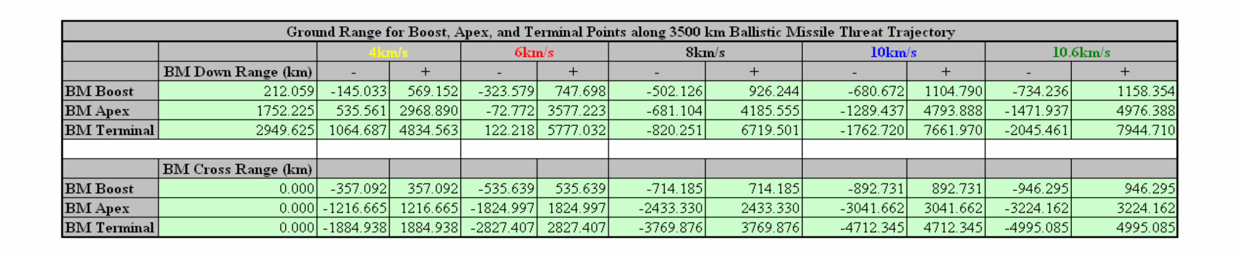
From these current and near future velocities, 8 km/sec and 10 km/sec were selected as possible future capability in interceptor velocity. Upon finalization of the BM threat, model, and railgun interceptor model, 10.6 km/sec was added in this section of the report for comparative purposes only.

Tables 38 and 39 show the BM threat ground range and the corresponding interceptor range radii from the end of boost, apex, and end of midcourse (terminal) positions along the BM threat trajectory. The resulting down range and cross range points in Table 39 were used to plot the corresponding range rings for each of the corresponding interceptor velocities.



Maximum Interceptor Launch Ranges (km)				
	4km/s	6km/s	8km/s	10km/s
BM Boost	357.092	535.639	714.185	892.731
BM Apex	1216.665	1824.997	2433.330	3041.662
BM Terminal	1884.938	2827.407	3769.876	4712.345

Table 38. Maximum Interceptor Launch Ranges (km)



Ground Range for Boost, Apex, and Terminal Points along 3500 km Ballistic Missile Threat Trajectory											
		4km/s		6km/s		8km/s		10km/s		10.6km/s	
	BM Down Range (km)	-	+	-	+	-	+	-	+	-	+
BM Boost	212.059	-145.033	569.152	-323.579	747.698	-502.126	926.244	-680.672	1104.790	-734.236	1158.354
BM Apex	1752.225	535.561	2968.890	-72.772	3577.223	-681.104	4185.555	-1289.437	4793.888	-1471.937	4976.388
BM Terminal	2949.625	1064.687	4834.563	122.218	5777.032	-820.251	6719.501	-1762.720	7661.970	-2045.461	7944.710
	BM Cross Range (km)										
BM Boost	0.000	-357.092	357.092	-535.639	535.639	-714.185	714.185	-892.731	892.731	-946.295	946.295
BM Apex	0.000	-1216.665	1216.665	-1824.997	1824.997	-2433.330	2433.330	-3041.662	3041.662	-3224.162	3224.162
BM Terminal	0.000	-1884.938	1884.938	-2827.407	2827.407	-3769.876	3769.876	-4712.345	4712.345	-4995.085	4995.085

Table 39. Ground Range for Boost, Apex, and Terminal Points Along 3,500 km BM Threat Trajectory

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[88] Jane's Information Group, "RIM-66/-67/-156 Standard SM-1/-2 and RIM-161 Standard SM-3," *Jane's Strategic Weapon System*, http://www.janes.com, posted 7 April 2005.

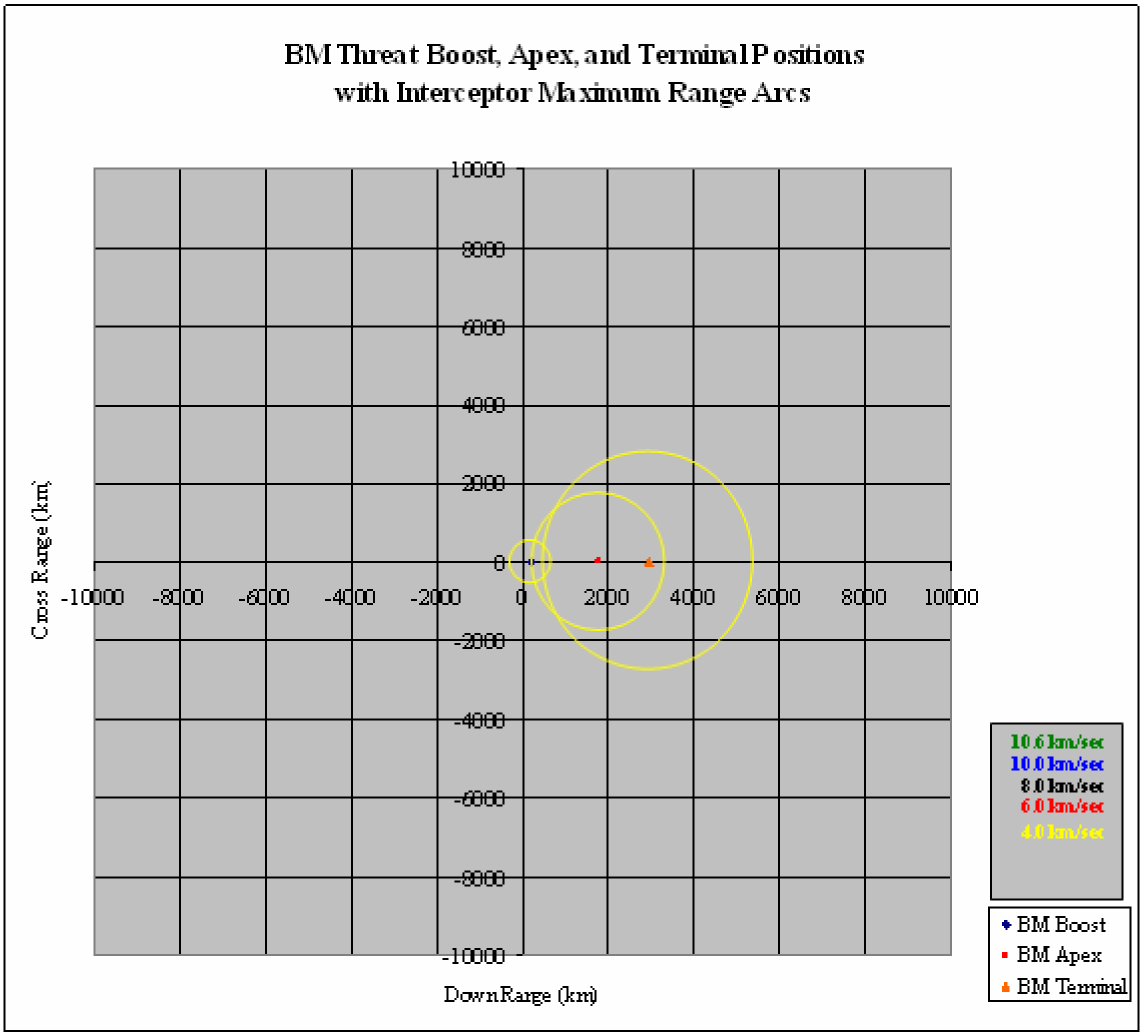

Figure 143. BM Threat Boost, Apex, and Terminal Positions with 4-km/sec Interceptor Maximum Range Arcs

At velocities of 4 km/sec, there is a very small area of overlap where a ship would be in a position to intercept the BM during all phases of its flight (Figure 143). This would present a ship's operating box approximately 535 km to 569 km, or 34 km beginning at 535 km down range from the launch site and 350 km on either side of the BM trajectory. This velocity is not feasible for an effective BMD, since it requires the knowledge of the active BM launch site and the designated target along a maximum range flight path. BMs that are capable of achieving burnout velocities similar to the

3.7 km/sec of the Taepo Dong 1 cannot be engaged if the threat missile launch creates a tail chase situation.[89]

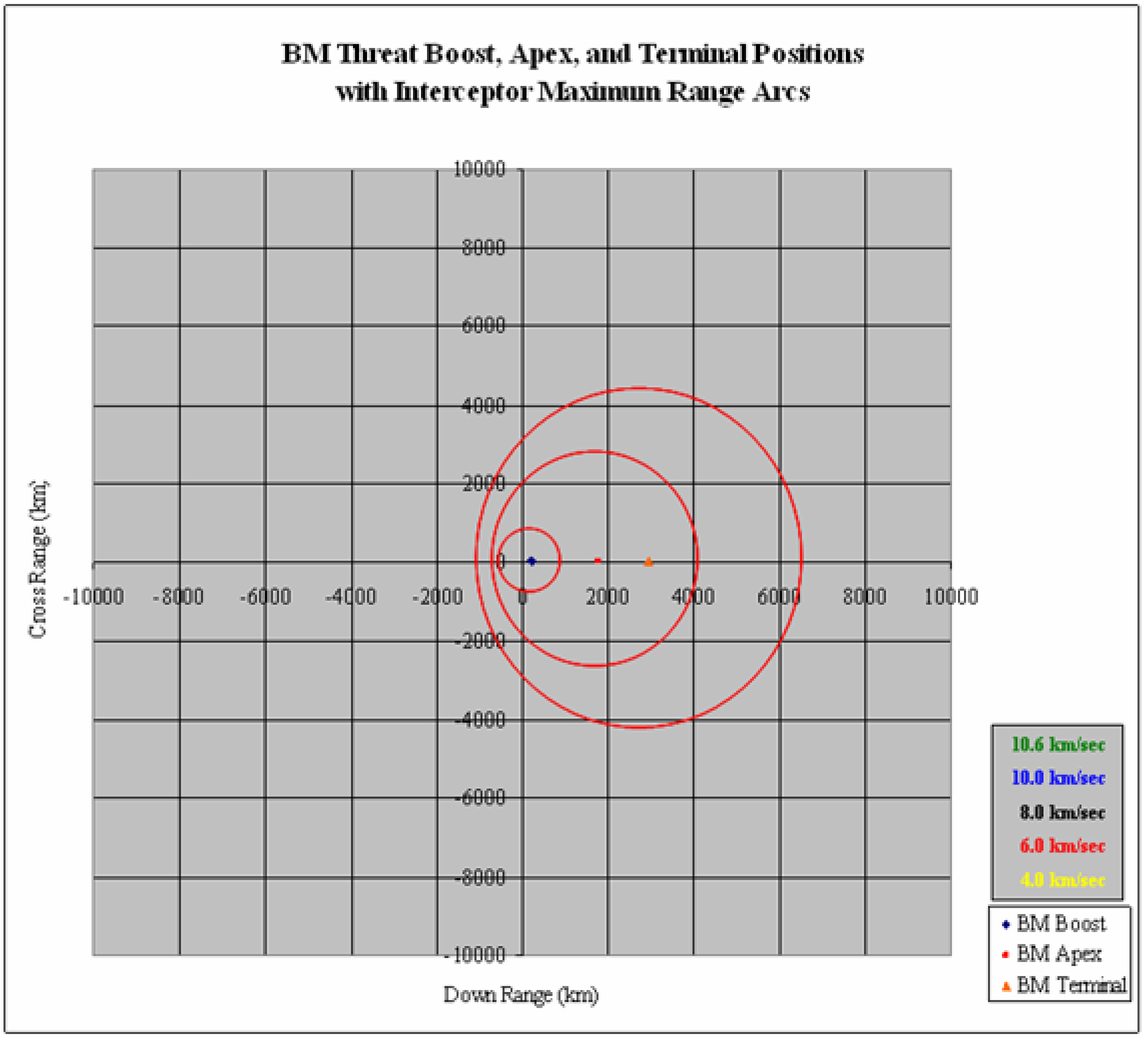

Figure 144. BM Threat Boost, Apex, and Terminal Positions with 6-km/sec Interceptor Maximum Range Arcs

At velocities of 6 km/sec, the range circle that enables the intercept of the threat during its boost phase is completely within the other range circles giving a larger operating area to intercept the BM during all phases of its flight (Figure 144). This would present a ship's operating area within an approximate 800-km arc from the launch site. This velocity seems to be feasible for an effective BMD. However, its effectiveness is highly dependent on the direction of the BM launch. With BMs, such as the

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[89] Dean A. Wilkening, "Airborne Boost-Phase Ballistic Missile Defense," *Science and Global Security*, 12:1-67, 2004, p. 61.

Taepo Dong 2, reaching burnout velocities of 5.0 km/sec, making a tail chase engagement very difficult and requiring the ship be relatively close to the launch site, since it requires the knowledge of the active BM launch site and the designated target along a maximum range flight path.[90]

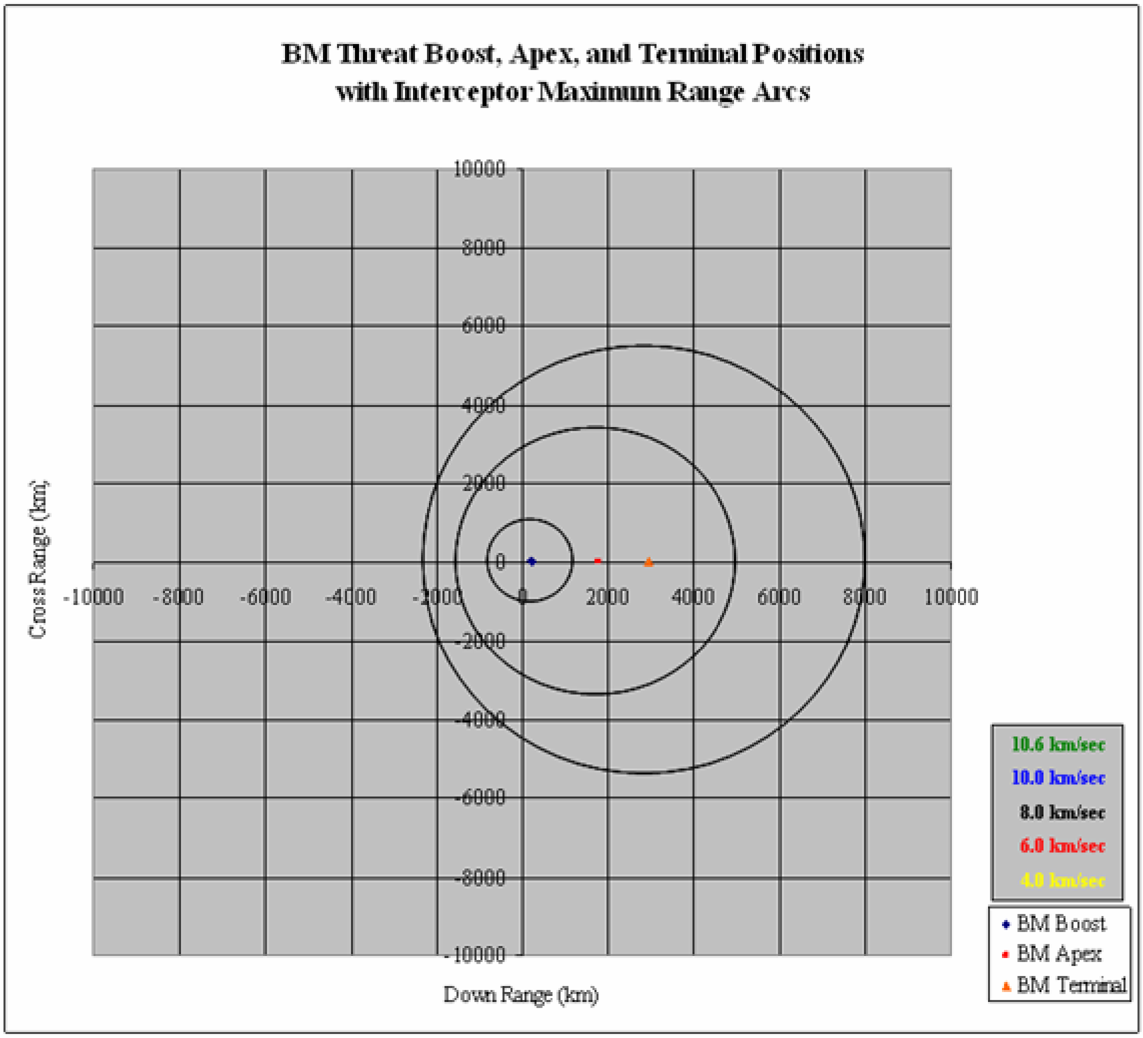

Figure 145. BM Threat Boost, Apex, and Terminal Positions with 8-km/sec Interceptor Maximum Range Arcs

At velocities of 8 km/sec, the range circle that enables the intercept of the threat during its boost phase is completely within the other range circles giving a larger operating area to intercept the BM during all phases of its flight (Figure 145). This would present a ship's operating area within an approximate 1,100-km arc from the

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[90] Dean A. Wilkening, "Airborne Boost-Phase Ballistic Missile Defense," *Science and Global Security*, 12:1-67, 2004, p. 61.

launch site. This velocity is feasible for an effective BMD. Its effectiveness is less dependent on the direction of the BM launch and, even with BMs such as the Taepo Dong 2, a tail chase engagement is possible for an approximate 2,000-km tail chase.

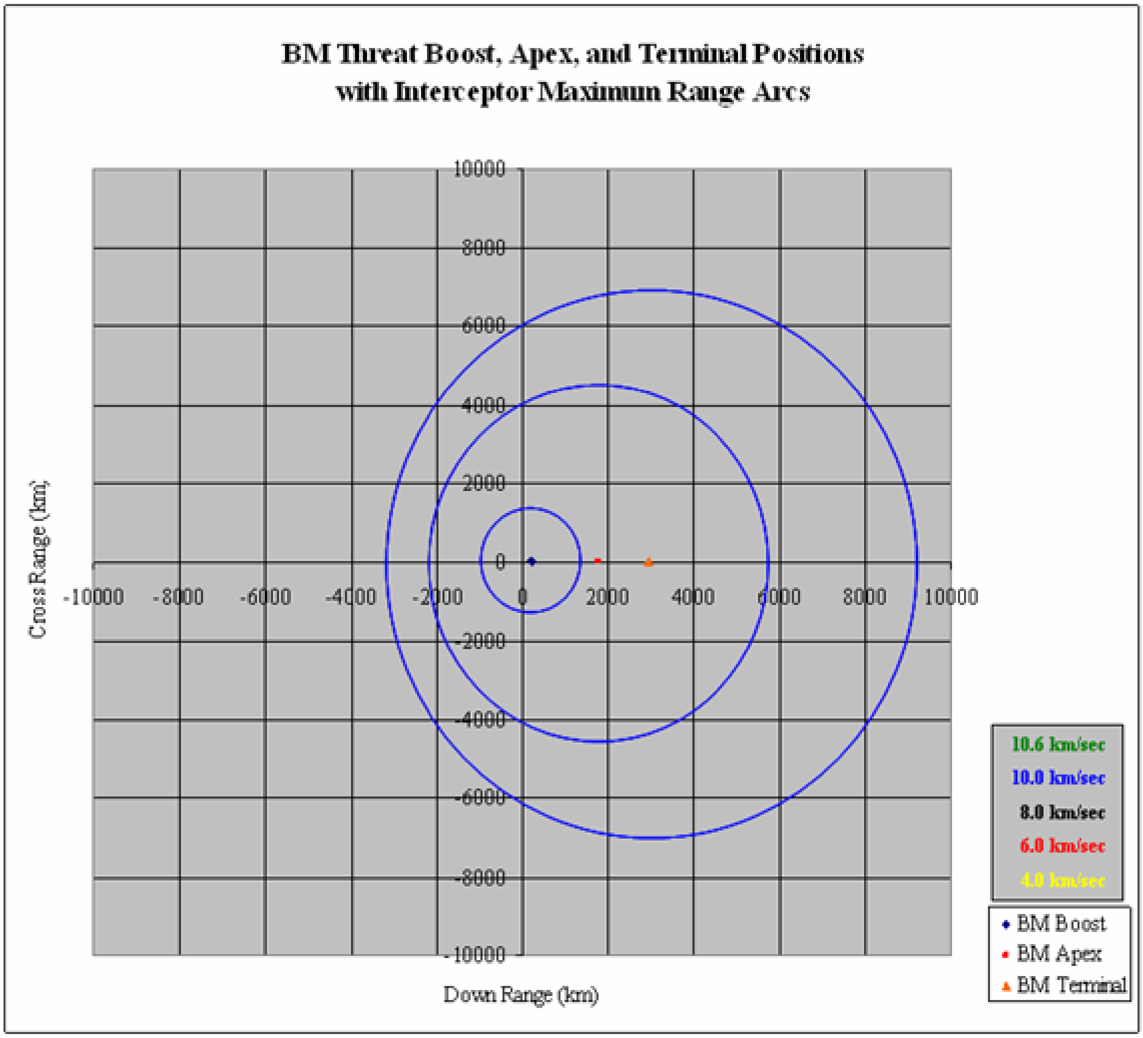


Figure 146. BM Threat Boost, Apex, and Terminal Positions with 10-km/sec Interceptor Maximum Range Arcs

At velocities of 10 km/sec, the range circle that enables the intercept of the threat during its boost phase is completely within the other range circles, giving a larger operating area to intercept the BM during all phases of its flight (Figure 146). This would present a ship's operating area within an approximate 1,400-km arc from the launch site. This velocity is feasible for an effective BMD. Its effectiveness is less dependent on the direction of the BM launch and, even with BMs such as the

Taepo Dong 2, a tail chase engagement is possible for an approximate 3,000-km tail chase.

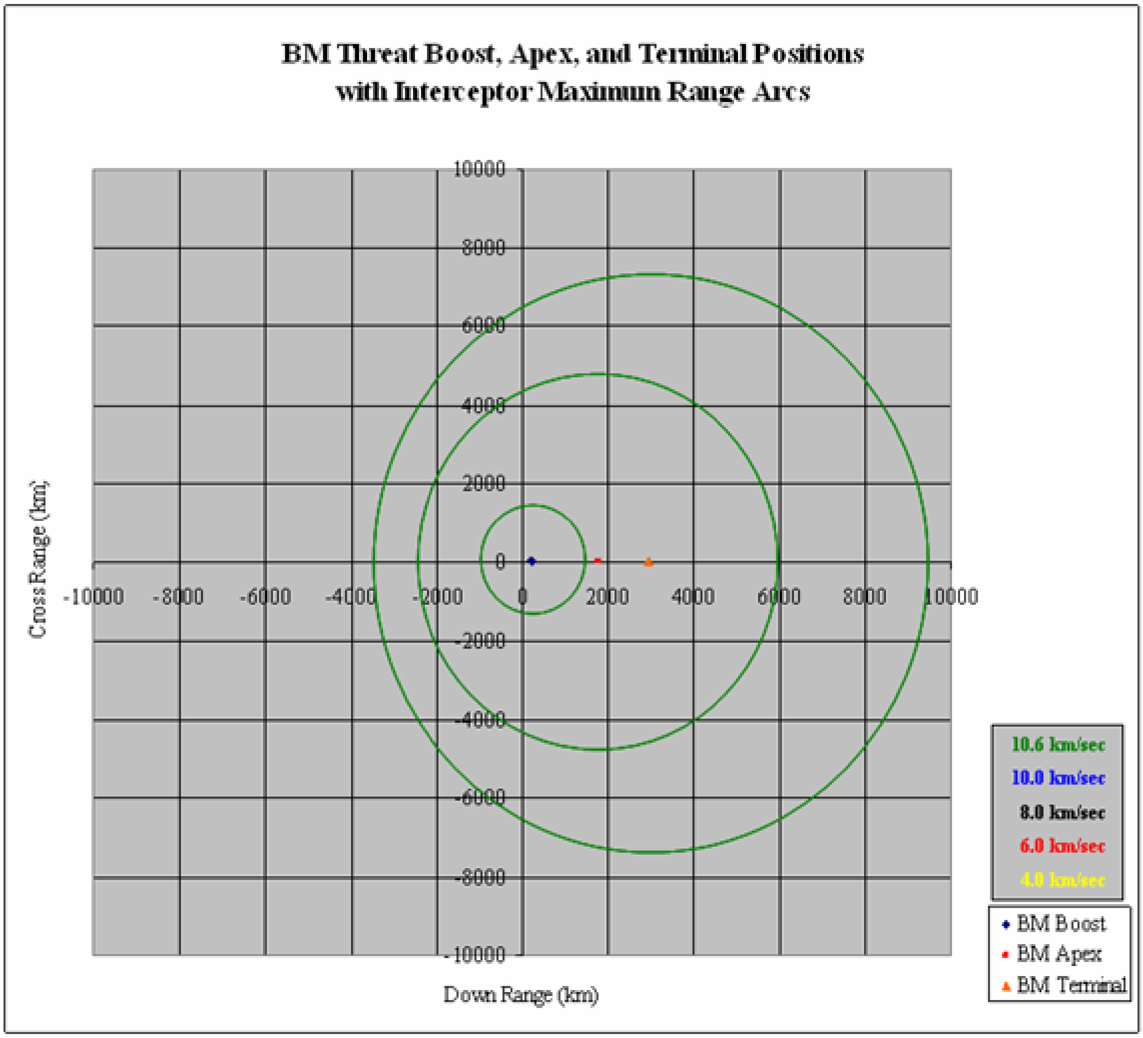


Figure 147. BM Threat Boost, Apex, and Terminal Positions with 10.6-km/sec Interceptor Maximum Range Arcs

At velocities of 10.6 km/sec, the range circle that enables the intercept of the threat during its boost phase is completely within the other range circles giving a larger operating area to intercept the BM during all phases of its flight (Figure 147). This would present a ship's operating area within an approximate 1,500-km arc from the launch site. This velocity is feasible for an effective BMD. Its effectiveness is less dependent on the direction of the BM launch and, even with BMs such as the Taepo Dong 2, a tail chase engagement is possible for an approximate 3,500-km tail chase.

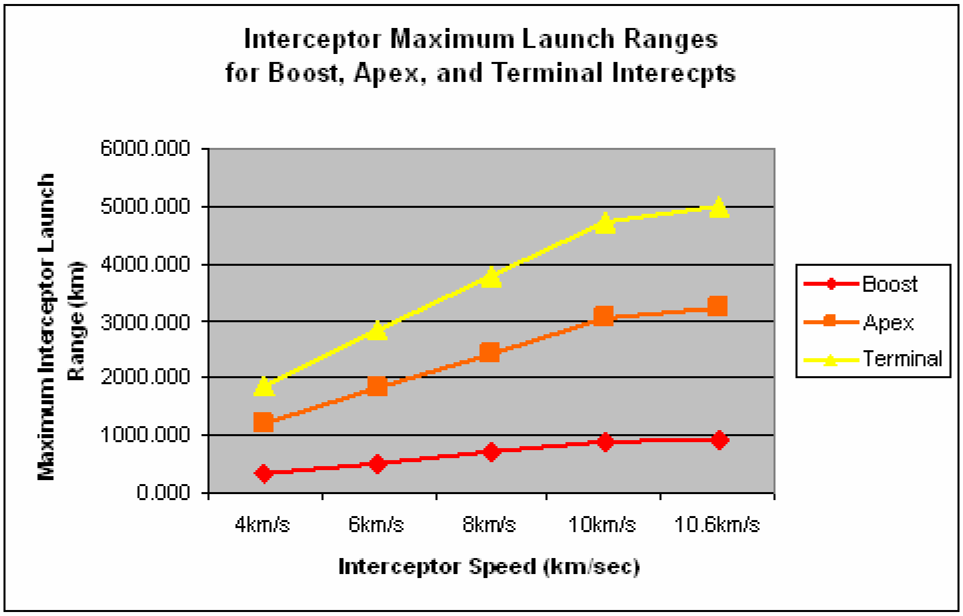
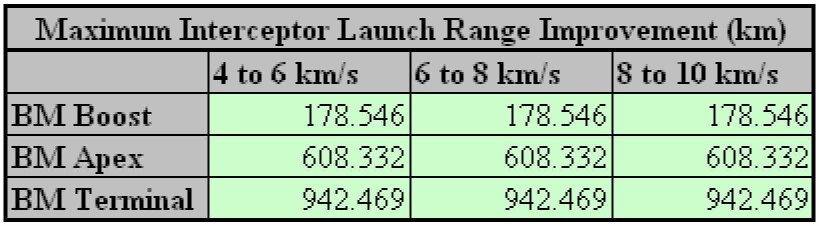


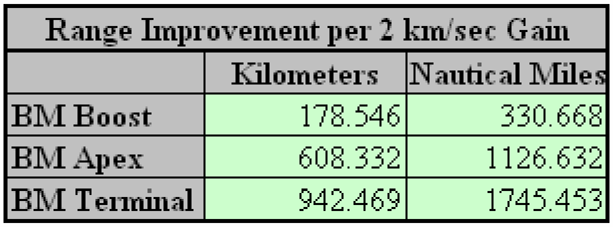
Figure 148. Interceptor Maximum Lunch Ranges for Boost, Apex, and Terminal Intercepts

Analysis of each of the interceptor velocities and their respective maximum launch ranges show a linear relationship for each integer change in interceptor velocity, as shown in Figure 148 and Tables 40 and 41.



Maximum Interceptor Launch Range Improvement (km)			
	4 to 6 km/s	6 to 8 km/s	8 to 10 km/s
BM Boost	178.546	178.546	178.546
BM Apex	608.332	608.332	608.332
BM Terminal	942.469	942.469	942.469

Table 40. Maximum Interceptor Launch Range Improvement (km)

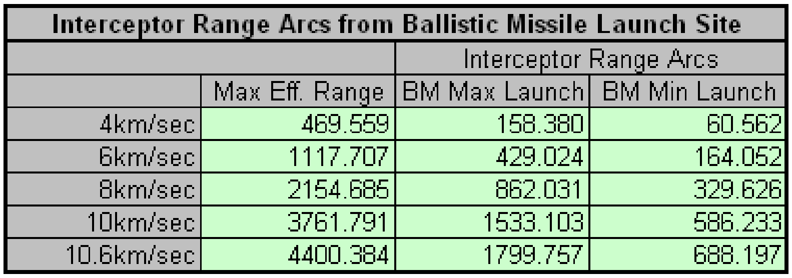


Range Improvement per 2 km/sec Gain		
	Kilometers	Nautical Miles
BM Boost	178.546	330.668
BM Apex	608.332	1126.632
BM Terminal	942.469	1745.453

Table 41. Range Improvement per 2 km/sec Gain

During engagements where time is the critical factor, the operating area gained by an increase in interceptor velocity provides a vital contribution to a ships capability to operate in a multimission environment.

Table 42 represents approximated interceptor range arcs for various interceptor velocities. The ranges shown for the 4-km/sec interceptor versus a BM fired at a target 3,500 km from the launch site is not accurate if intercept of the threat is desired at any point along the BM’s trajectory. As shown in Figure 143, there is little overlap of the interceptor range circles, therefore intercept along the entire trajectory for the 4-km/sec interceptor is not possible. For the remaining interceptor velocities, these ranges provide an approximation for ship operating areas from known launch sites.



Interceptor Range Arcs from Ballistic Missile Launch Site

		Interceptor Range Arcs	
	Max Eff. Range	BM Max Launch	BM Min Launch
4km/sec	469.559	158.380	60.562
6km/sec	1117.707	429.024	164.052
8km/sec	2154.685	862.031	329.626
10km/sec	3761.791	1533.103	586.233
10.6km/sec	4400.384	1799.757	688.197

Table 42. Interceptor Range Arcs from BM Launch Site

The 10-km/sec interceptor was ultimately selected through modeling and simulation as part of the overall conceptual design. The ability of a ship to deliver a 10km/sec interceptor against an intermediate-range BM threat brings with it the ability for that ship to have a patrol area within an arc of 1,400 km from a given launch site. To put this distance into perspective, the maritime coastline of Iran is approximately 1,500 km and its farthest land border from the Persian Gulf is approximately 1,300 km. A single ship fielding a 10-km/sec interceptor could feasibly be anywhere along the coast of Iran and intercept an intermediate-range BM fired at a target near it’s maximum range capability of 3,500 km and consummate an intercept of the threat missile at any point along its trajectory. The 10-km/sec interceptor versus a minimum range launch allows for a ship to operate in an area within an arc of approximately 580 km from a given launch site, indicating that three ships may be necessary to cover the same coastal area, but lacks the over land coverage area.

6.5.2 Effects of Interceptor Probability of Single Shot Kill on Overall System Effectiveness

The overall probability of kill for a given salvo, assuming that all shots are statistically independent of each other and have an equal probability of kill, can be calculated using the equation $P(k) = 1 - (1 - P_{ssk})^n$, where n is the number of shots per salvo and P_{ssk} is the probability of single shot kill.[91]

The overall probability of kill P(k) takes incorporates the conditional probability that the warhead has been detected and tracked and can therefore be represented as $P(kill|track) = 1 - (1 - k_w)^n$, where k_w is the probability of a single shot killing the warhead.

Defensive effectiveness can be calculated based on a Bernoulli trial problem where the probability, P(X), that attacking warheads, x, will penetrate the defense is given by the binomial distribution $P(X) = \binom{W}{x}(1 - k_w)^x \left(k_w\right)^{W-x}$. When X=0, the overall effectiveness of the defensive system can be determined and the binomial equation reduces to $P(0) = \left(k_w\right)^W$.

From $P(kill_{overall}) = P(track)P(kill|track)$, $P(kill|track) = 1 - (1 - k_w)^n$, and $P(0) = \left(k_w\right)^W$ the number of interceptors needed to achieve a given overall system capability can be derived and is represented by the equation,

$$n = \frac{\ln\left(1 - \dfrac{P(0)^{1/W}}{P_w(track)}\right)}{\ln\left(1 - k_w\right)},$$

where P(0)=Overall system capability, P_w(track)=Probability of tracking the warhead, k_w=Probability of killing the warhead, W=number of warheads, and n=number of interceptors needed.[92] Figure 149 shows the number of interceptors needed for various

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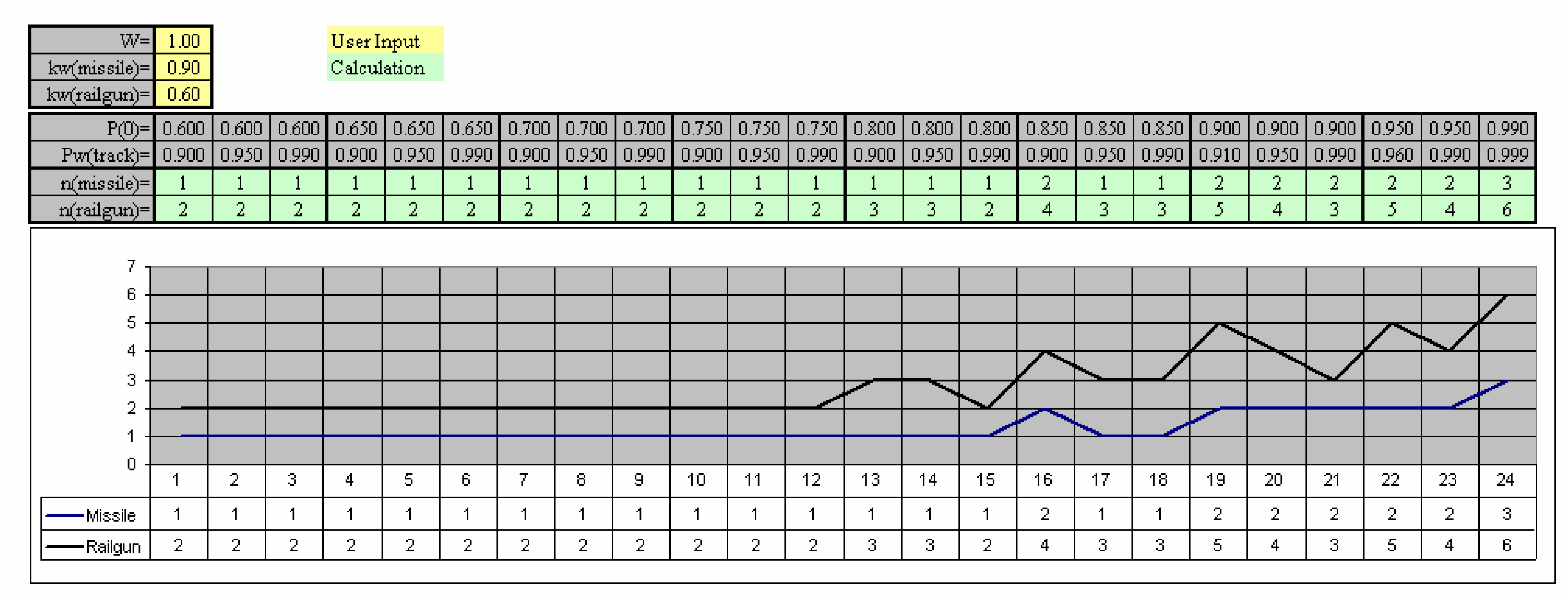
[91] Daniel H. Wagner, W. Charles Mylander, and Thomas J. Sanders, *Naval Operations Analysis Third Edition*, Naval Institute Press, Annapolis, MD, 1999, pp. 133-134.

[92] Dean A. Wilkening, “A Simple Model for Calculating Ballistic Missile Defense Effectiveness,” *Science and Global Security*, Vol. 8:2, 1999, p. 205.

P(0) and P_w(track) values given a missile k_w of 0.90 and a railgun k_w of 0.60 versus a single warhead, W.



W=	1.00
kw(missile)=	0.90
kw(railgun)=	0.60

User Input

Calculation

P(0)=	0.600	0.600	0.600	0.650	0.650	0.650	0.700	0.700	0.700	0.750	0.750	0.750	0.800	0.800	0.800	0.850	0.850	0.850	0.900	0.900	0.900	0.950	0.950	0.990
Pw(track)=	0.900	0.950	0.990	0.900	0.950	0.990	0.900	0.950	0.990	0.900	0.950	0.990	0.900	0.950	0.990	0.900	0.950	0.990	0.910	0.950	0.990	0.960	0.990	0.999
n(missile)=	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	2	2	2	2	2	3
n(railgun)=	2	2	2	2	2	2	2	2	2	2	2	2	3	3	2	4	3	3	5	4	3	5	4	6

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Missile	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	2	2	2	2	2	3
Railgun	2	2	2	2	2	2	2	2	2	2	2	2	3	3	2	4	3	3	5	4	3	5	4	6

Figure 149. Required number of interceptors, n, to achieve a desired P(0) at various Required values for P_w(track).

During simulation, an overall effectiveness of 0.90 was desired and the corresponding salvo sizes were used given a probability of tracking the warhead of 0.95. These salvo sizes, in addition to the firing rate of the weapon system in Table 43, were then implemented into the required engagement time for each warhead. The ranges and launch to end-of-midcourse times were averaged across all four final scenarios and used to approximate the maximum number of BMs (or warheads) that could be simultaneously in-flight and engaged by the system. The average ranges and flight times are valid only under ideal conditions, where the missiles were launched along a trajectory as to pass over the defensive position. However, the number of BMs obtained was used in the scenarios as the starting point to determine the saturation point of this system.

Weapon Load:	
80	Missiles
1200	Railgun Rounds (600 per mount)
Total Engagements @ 90% Effective)	
40	Missile Engagements
300	Railgun Engagements
7.50 : 1	Railgun:Missile Engagements
Total Number of Engagements/Ship	
0.60	P(kill)
20	rounds per minute
4	rounds per engagments @ 90% Effective
15	engagements per mount per min
2	number of mounts
30	engagements per min per ship
8.48	minutes average time to terminal
1699.00	km average range of BM flight
254	Estimated BM's simultaneously in flight
1016	Railgun Rounds needed
46	Number of Engagements Remaining Onbd

Table 43. Weapon Load

To further define the overall system's effectiveness sensitivity to the number of interceptors fired against BMs in flight, given a specified P_w(track) at various probabilities of killing the warhead (P_{ssk} or k_w), the equation $P(0) = P(kill_{overall}) = \left[P_w(track)\left(1-\left(1-k_w\right)^n\right)\right]^W$ was used to determine the system's sensitivity and is shown in Figure 150.

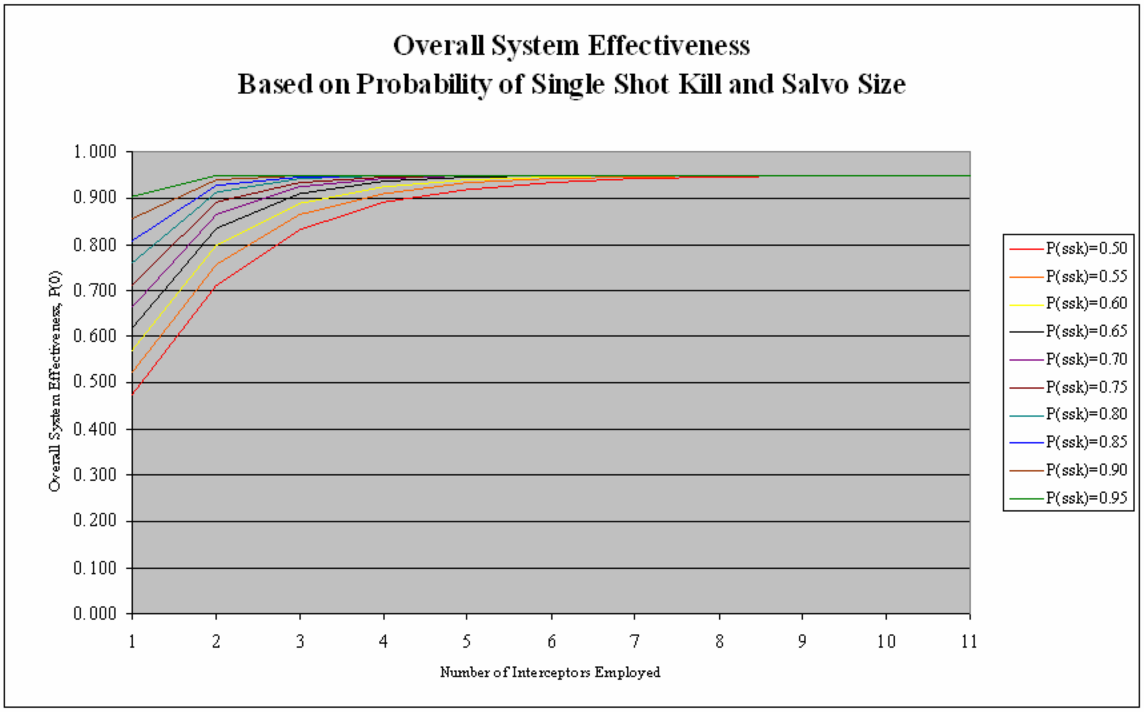


Figure 150. P(0) When P_w(track)=0.95, W=1

The systems negation capability falls below 0.50 when P_w(track)=0.95 and 0.99 when the number of warheads, W, exceeds 14 and 70, respectively, and is illustrated in Figures 151 and 152.

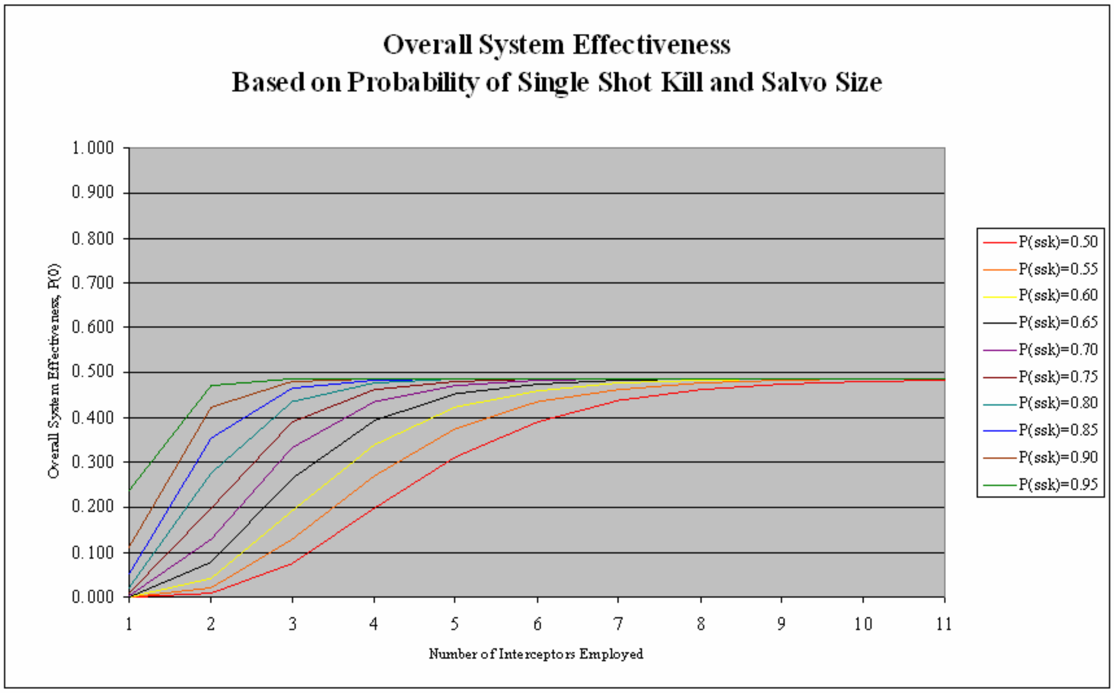


Figure 151. P(0) When P_w(track)=0.95, W=14

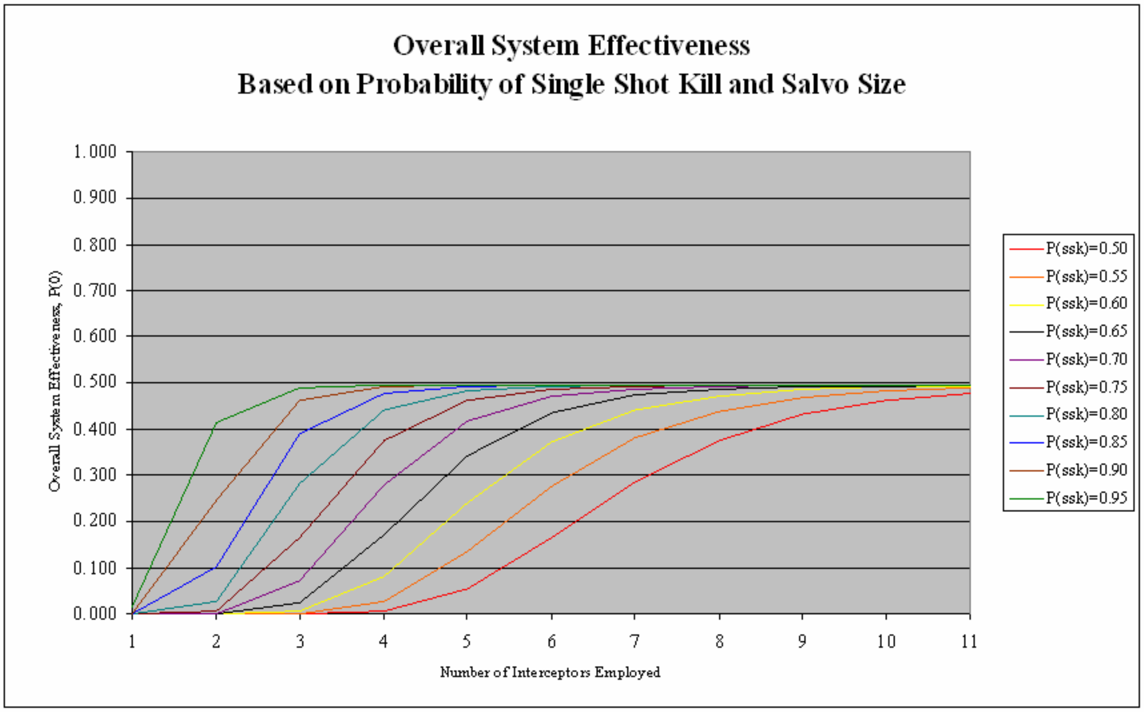


Figure 152. P(0) When P_w(track)=0.99, W=70

Figure 149 illustrates the systems overall capability when W=1 and P_w(track)=0.95. With improvements in interceptor k_w, there is the intuitive result of smaller salvo sizes. The reduction of salvo size has cascading effects by reducing the overall cost per engagement, adding depth to the magazine, and increasing the total number of possible engagements by the weapon. A key consideration to investing in an increased k_w for the interceptors is that, regardless of the k_w achieved by the interceptor, the overall system effectiveness, or negation capability, it can never exceed the system's ability to track the warhead.

Figure 153 and Table 44 demonstrate the relationship between salvo size and overall system effectiveness when W=1 and P_w(track)=0.999. P_w(track) was set to 0.999 in order to show the relationship at a P(0) of 0.99, recall that the overall system effectiveness can never exceed the system's ability to track the warhead. From Table 44, tradeoffs can be made between investing in an improvement of an interceptors k_w or a sensors P_w(track) can be intuitively made based on the overlapping salvo sizes observed due to the relationship between k_w and P(0).

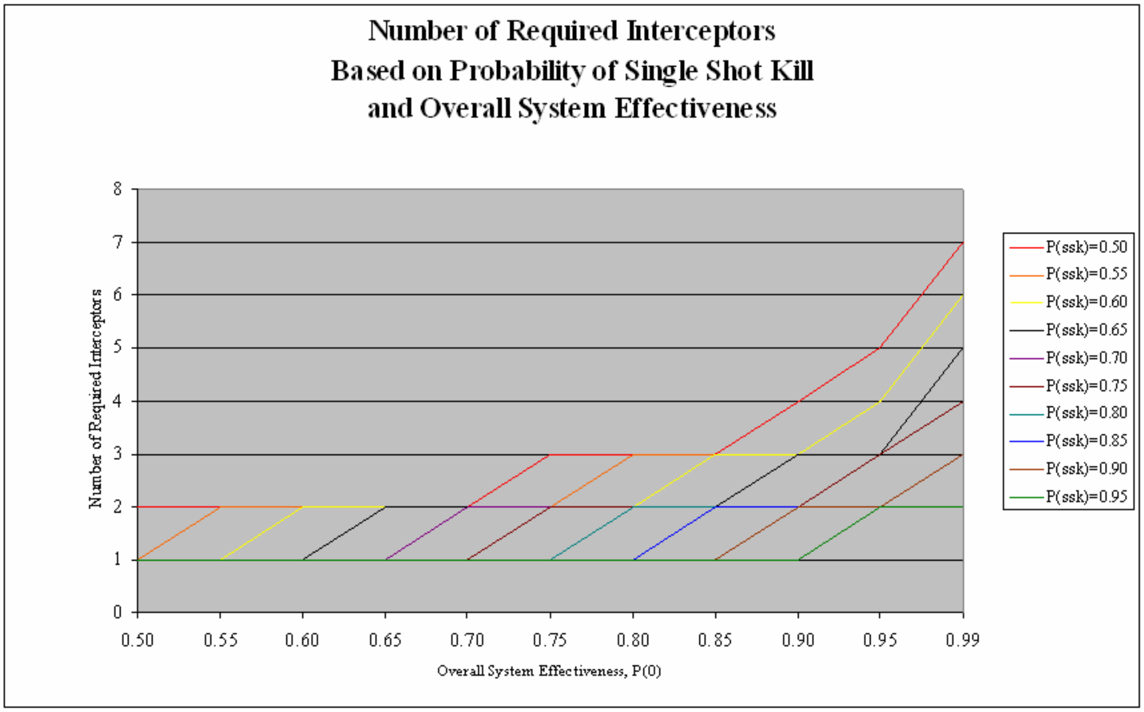
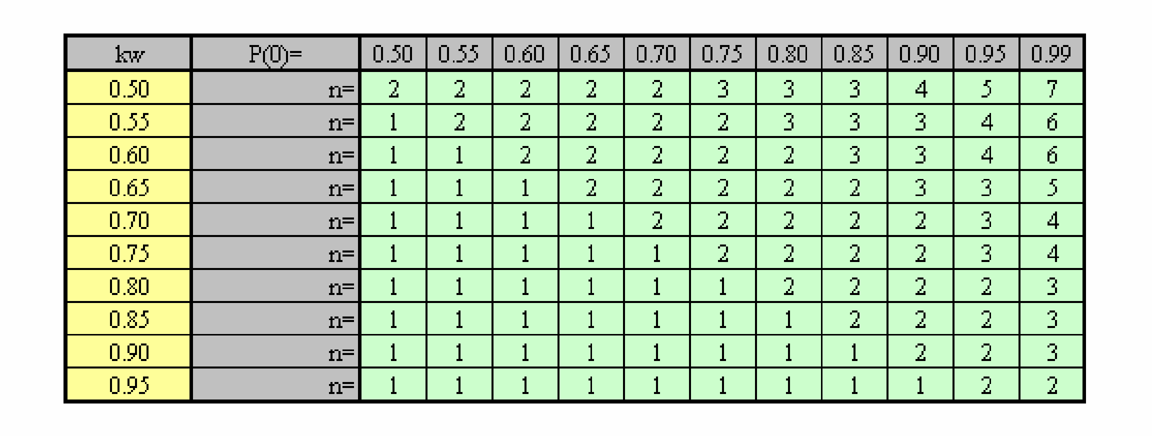


Figure 153. Required Number of Interceptors, n, When P_w(track)=0.999, W=1 to Achieve a Desired P(0)



kw	P(0)=	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	0.99
0.50	n=	2	2	2	2	2	3	3	3	4	5	7
0.55	n=	1	2	2	2	2	2	3	3	3	4	6
0.60	n=	1	1	2	2	2	2	2	3	3	4	6
0.65	n=	1	1	1	2	2	2	2	2	3	3	5
0.70	n=	1	1	1	1	2	2	2	2	2	3	4
0.75	n=	1	1	1	1	1	2	2	2	2	3	4
0.80	n=	1	1	1	1	1	1	2	2	2	2	3
0.85	n=	1	1	1	1	1	1	1	2	2	2	3
0.90	n=	1	1	1	1	1	1	1	1	2	2	3
0.95	n=	1	1	1	1	1	1	1	1	1	2	2

Table 44. Required Number of interceptors, n, When Pw(track)=0.999, W=1 to Achieve a Desired P(0)

The systems sensitivity to different key aspects of an interceptor's velocity and probability of single shot kill and the overall system effectiveness are obvious. With higher velocities, the ability to defend a larger area from a larger area of patrol is a substantial benefit. This benefit is especially noticed in regions of the world where large areas of water space are simply not available. It has also been shown that the system's overall capability can never exceed the system's ability to track the BM warhead. When an improvement in the system's overall capability is desired, consideration must be made to the resulting salvo size of that improvement and whether an increase in the system's ability to track the warhead or improvement in the interceptor's ability to kill the warhead is more beneficial; in some cases, improvement in both areas may be the most beneficial.

6.6 RISK ASSESSMENT

In this study, the conceptual design involves technologies that are currently in early technology readiness levels (TRL) of TRL 2 (SOTS-conformable radar) and TRL 4 (railgun and railgun projectile).[93] Should the needs, requirements, and actual concept of the SABR design be actually pursued as system to be developed, a full risk assessment would be required.

Since the conceptual SABR system focuses only on technologies to meet future needs, the elements of risk factors related to system technologies are addressed. The complications of personnel, production, and budget—normally significant considerations—would be accounted during future system development. At the very least, indications of future risk assessments and mitigation plans can be described.

Since the focus of the SABR conceptual system is comprised of several key components integrated for the common purpose of BMD, the risk assessment includes only those relevant aspects taken in the context of the system as a whole. To fully evaluate the potential risks of the system, each major individual component must be examined. In the case of the SABR system, the major components include:

- MFPAR
- SOTS Conformable Radar
- ABMS
- CIX
- Railgun
- Railgun Projectile
- Seaframe

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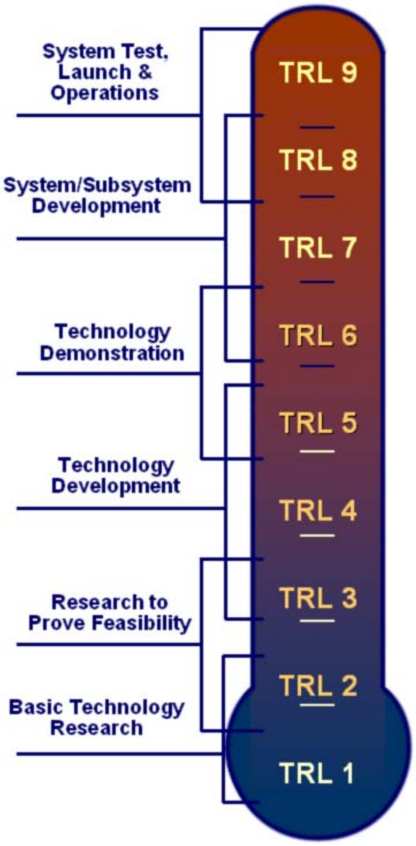
[93] TRL definitions taken from NASA, "ECS TRL Description," http://ecs.arc.nasa.gov/other/TRL.htm, May 2006. Specific TRL values for SOTSR and railgun systems were assigned by the SABR team.

Each of these components require analysis to determine their total Risk Factor (RF) based on the probabilities of risks involved in the technology maturity (P_M), complexity (P_C), and dependency (P_D) on the other component(s) of the system. Probabilities for each component are computed and assigned based on risk severity. The values for these probabilities are on graduated scale between 0.1 and 0.9. Each value corresponds to the TRL scale shown in Figure 154.



TRL 9: Actual system "operationally proven" through successful mission operations Thoroughly debugged software. Fully integrated with operational hardware/software systems. All documentation completed. Successful operational experience. Sustaining software engineering support in place. Actual system fully demonstrated.

TRL 8: Actual system completed and "operationally qualified" through test and demonstration (Simulated or Operational) Thoroughly debugged software. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. V&V completed.

TRL 7: System prototype demonstration in an operational environment Most functionality available for demonstration and test. Well integrated with operational hardware/software systems. Most software bugs removed. Limited documentation available.

TRL 6: System/subsystem model or prototype demonstration in a relevant environment (Simulated or Operational) Prototype implementations on full scale realistic problems. Partially integrated with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.

TRL 5: Component and/or breadboard validation in relevant environment Prototype implementations. Experiments with realistic problems. Simulated interfaces to existing systems.

TRL 4: Component and/or breadboard validation in laboratory environment Standalone prototype implementations. Experiments with full scale problems or data sets.

TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept Limited functionality implementations. Experiments with small representative data sets. Scientific feasibility fully demonstrated.

TRL 2: Technology concept and/or application formulated Basic principles coded. Experiments with synthetic data. Mostly applied research.

TRL 1: Basic principles observed and reported Basic properties of algorithms, representations, and concepts. Mathematical formulations. Mix of basic and applied research.

Figure 154. TRL Scale Description

Explanations for each value assigned are outlined in the maturity, complexity, and dependency factor risk tables shown in Tables 45 through 47.

	Maturity Facor (P_M)						
magnitude	**MFPAR**	**Conformable SOTS EW Radar**	**ABMS**	**CIX**	**Railgun**	**Railgun Projectile**	**Seaframe**
0.1 (TRL 8&9)							
0.3 (TRL 7)	Minor redesign						Minor redesign
0.5 (TRL 5&6)				Similar technology available; major change feasible		Similar technology available; major change feasible	
0.7 (TRL 3&4)			Technology available; complex design		Technology available; complex design		
0.9 (TRL 1&2)		State of the art (further research required)					

Table 45. Maturity Factor Risk

	Complexity Factor (P_C)						
magnitude	**MFPAR**	**Conformable SOTS EW Radar**	**ABMS**	**CIX**	**Railgun**	**Railgun Projectile**	**Seaframe**
0.1 (TRL 8&9)							
0.3 (TRL 7)	Minor increases in complexity					Minor increases in complexity	Minor increases in complexity
0.5 (TRL 5&6)			Moderate increase in complexity	Moderate increase in complexity			
0.7 (TRL 3&4)					Significant increase in complexity		
0.9 (TRL 1&2)		Extremely complex					

Table 46. Complexity Factor Risk

	Dependency Factor (P_D)						
magnitude	**MFPAR**	**Conformable SOTS EW Radar**	**ABMS**	**CIX**	**Railgun**	**Railgun Projectile**	**Seaframe**
0.1 (TRL 8&9)	Independent of existing systems			Independent of existing system		Independent of existing systems	Independent of existing systems
0.3 (TRL 7)		Performance dependent on compatibility with MF PA radar			Performance dependent on compatibility with ABMS		
0.5 (TRL 5&6)			Performance dependent on compatibility with existing systems and functionality of CIX				
0.7 (TRL 3&4)							
0.9 (TRL 1&2)							

Table 47. Complexity Factor Risk

To determine the overall combined risk factor for the individual components of the SABR system, the following equation was used:

$$\text{Risk Factor (RF)} = P_f + C_f - (P_f)(C_f),$$

where P_f is the probability of failure and C_f is the consequence of failure.[94] Further breaking down the equation

$$P_f = a(P_M) + b(P_C) + c(P_D),$$

where a, b, and c are weighing factors whose sum equals one.

Consequence of failure breaks down in similar fashion:

$$C_f = d(C_t) + e(C_c) + f(C_s),$$

where C_t equals the consequence of failure due to technical factors, C_c equals the consequence of failure due to changes in cost, and C_s equals the consequence of failure due to changes in the schedule. As with P_f, d, e, and f are weighing factors whose sum equals one.

Since the SABR system is conceptual in nature and is not in production, C_f equals zero as there are no changes in technical factors, no cost changes, and no schedule to be ahead or behind of. As such, the final equation used to determine the risk factors for the SABR system is

$$\text{Risk Factor (RF)} = a(P_M) + b(P_C) + c(P_D).$$

Using weighing factors for Maturity Factor (a), Complexity Factor (b), and Dependency Factor (c) of 0.25, 0.55, and 0.2, respectively, individual risk factors for each SABR component can be computed by substituting the corresponding values from the previous risk tables. Based on this, Table 48 shows the calculated risk factors by component:

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[94] Defense Systems Management College, *Systems Engineering Management Guide*, Fort Belvoir, VA, 1986, in B. Blanchard and W. Fabrycky, *Systems Engineering and Analysis*, 3rd ed., Upper Saddle River: Prentice-Hall, 1998, p. 658.

Risk Factors by Component	
MFPAR	0.26
Conformable SOTSR	
ABMS	0.55
CIX	0.42
Railgun	0.62
Railgun Projectile	0.31
Seaframe	0.26

Table 48. Calculated Risk Factors

Having determined the risk factors of each component of the SABR system, each value is then applied to risk analysis and reporting flow chart to determine the best course of action for risk management should the system be developed beyond the conceptual phase. Figure 155 is the chart to which each risk factor was applied.

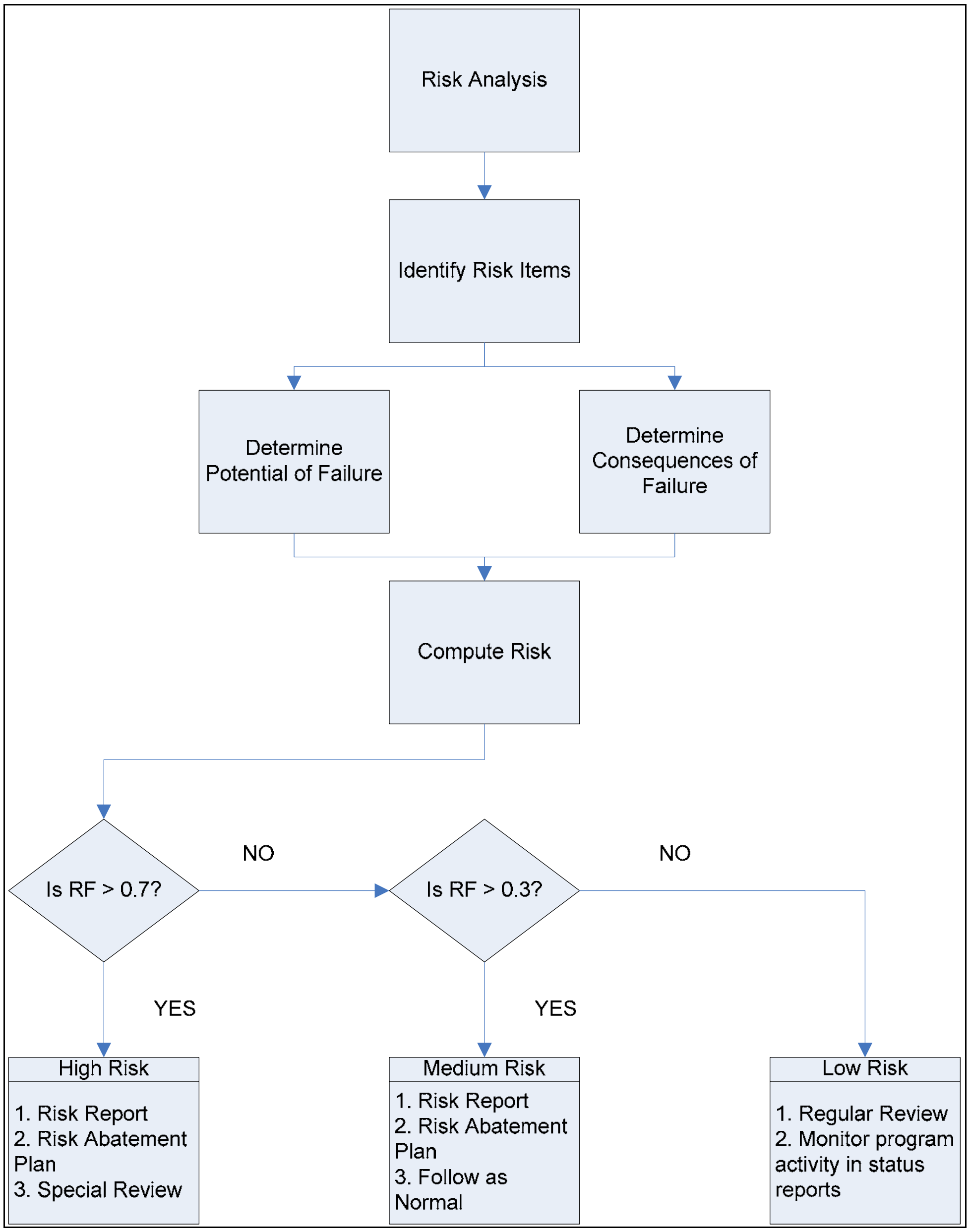

Figure 155. Risk Analysis and Reporting Procedure Flow Chart

Following this chart, Table 49 shows the risk levels for each SABR component.

Risk Levels by Component	
MFPAR	LOW RISK
Conformable SOTSR	HIGH RISK
ABMS	MEDIUM RISK
CIX	MEDIUM RISK
Railgun	MEDIUM RISK
Railgun Projectile	MEDIUM RISK
Seaframe	LOW RISK

Table 49. SABR System Component Risk Levels

Should the SABR system be developed as system for production, it is recommended that risk reports and risk abatement plans be made for all system components except for the Seaframe and the MFPAR. Risk management for these two components can be managed under regular program reviews. Special attention should be given to both the Conformable SOTSR and interceptor components, as they are probably critical path issues for system development and production.

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7.0 CONCLUSIONS/CLOSING REMARKS

7.1 CONCLUSIONS

There are many critical factors and takeaways from this integrated BMD study. Aside from the SE processes, analysis of alternatives, model formulation, simulation runs, simulative analysis, cost analysis, and CONOPS, the following items are the ground truths of the study.

Organic sensors (even state-of-the-art sensors, such the conformable SOTS early warning radar) can only detect 50%-60% of launched BMs, at best.

Nonorganic sensors are essential to the detection and tracking of threat BMs. Combined with the organic sensors of the seaframe, BMs are detected nearly 100% of the time, regardless if there are 1 or 300 in flight simultaneously.

The most critical aspect of BMD is time. The faster a threat BM is detected, the faster that information travels to all players in the coordinated BMD, the faster engagement (C2) decisions can be made, and the faster an interceptor can be employed (and reemployed, if required). Improvements in any or all of these aspects, and the time it takes to conduct BDA, can only improve the probability of kill.

A CIX is critical to share all detection, identification, tracking, fire control (FC), and C2 information between all players in the BMD network. Inability to provide this critical information denies each player in the BMD network a common operational picture (COP) and ability to perform an intercept if they are determined to be the optimal asset for the engagement.

An ABMS is key to ensuring that the best player in the BMD network takes the "optimal shot" based on engageability, weapon system readiness and availability, and location of the player. This type of decision making aid reduces the amount of critical thinking required by BMD commanders (if he/she is "in the loop") and reduces the time table between detection and interceptor employment.

In the absence of nonorganic sensors, a combination of radars and sensor systems performs better than any individual sensor alone. The combination of the conformable

SOTS early warning radar and the MFPAR outperformed the MFPAR on its own by detecting an average of 10%-12% more of the total BMs in a threat salvo.[95]

Speed of the interceptor is critical aspect of BMD. Increased speed has direct correlation to probability of kill given an engagement and also to the probability of reengagement if required. Speed is also a critical enabler for engagement of BM threats that are not closing the general position of the BMD player. High speed projectiles expand the engageability window against crossing and tail-chase ballistic missile threats.

A multiple railgun system placement on the seaframe is the ideal configuration that combines the highest performance,[96] deepest magazines, with the lowest cost of operation.

Sea-based BMD is the first line of defense anywhere in the world. A SABR-enabled ship can be quickly moved into theatre, operate in international waters, and provide a credible defense against short- to intermediate-range BMs for the United States, U.S. forces, coalition partners, and friendly nations. Such flexibility would alleviate the burden on land and air based interceptors by providing a first-response ballistic missile negation percentage (% of BMs destroyed of the total threat salvo) of 43%-58% for a salvo up to 300 short- to intermediate-range BMs simultaneously.[97] Though this percentage appears small, the reality is that there are only a handful of nations that could coordinate a simultaneous BM salvo of this magnitude. It is far more likely that the missile launches would be staggered and smaller threat salvos and/or BMs launched in succession only improve these percentages. On the remote chance that a simultaneous 300-BM salvo can be launched, the negation percentage can be increased to approximately 90% by adding an additional SABR system ship to the 50-NM radius operating area of each ship originally on station.[98] Using the original three-ship

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[95] Based on results from the second iteration of simulations where nonorganic sensors had a probability of detection (P(d)) of zero.

[96] Based on the probability of kill given engagement (P(k | e)).

[97] Based on the probabilities of engagement (P(e)) multiplied by the probabilities of kill given engagement (P(k | e)) for the Middle Eastern and East Asian scenarios using a three-ship defense.

[98] Since the SABR model places a ship anywhere inside a 50-NM radius operating area, the addition of another ship inside this operating area would reflect the same as adding two more railguns and an additional magazine of 1,200 rounds. Based on this assumption, a linear association can be made from the 150 simultaneous missile saturation point and increase it to a 300 simultaneous missile saturation point.

operational employment, a simultaneous threat salvo of approximately 150 BMs or less provides a negation percentage of approximately 90%.

7.2 OPPORTUNITIES FOR FUTURE RESEARCH

Due to limited scope of this study, as well as time constraints, this study has only begun to tap the information available in the realm of BMD. Using the report as a basis for future studies, there is great potential for further research to be done in this field, both within NPS and from outside groups. The studies done by team SABR are just one of many studies concerning BMD, with plenty of opportunity for further research to be done by one of many organizations.

The TSSE group (located at NPS), which team SABR worked closely with during the development of a system, will be able to take specifications of radar and weapons systems, assess feasibility, adjust parameters as necessary, and design a seagoing platform capable of BMD.

In addition to TSSE, the students from TDSI, who are currently attached to NPS, will remain in Monterey working on thesis research after the completion of the SABR project. Working on individual theses, they will have the opportunity to further research in systems radar, interceptors, or operational research. From outside NPS, there are several agencies that may use the research of team SABR, and build on it.

The MDA, which is the successor to the SDI program initiated by President Regan, exists to "Develop and field an integrated BMDS capable of providing a layered defense for the homeland, deployed forces, friends, and allies against BMs of all ranges, in all phases of flight."[99] With such a mission statement, it is easy to see how such an agency might be interested in the research done thus far, and with the resources available to them, they will be able to build on, and greatly expand, what has already been done.

In addition to the above-mentioned MDA, further research could, and probably will be done by the U.S. Navy. As an integral part of the Sea Shield concept, BMD, specifically from a sea-based platform, is the interest of the Navy. This is addressed in

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[99] Missile Defense Agency Mission, http://www.mda.mil/mdalink/html/aboutus.html

the 2003 Naval Transformational Roadmap: "Efforts in ballistic missile defense will provide a completely new sea-based capability."[100]

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[100] Headquarters, Department of the Navy, Naval Transformation Roadmap 2003.

APPENDIX A: QUALITY FUNCTION DEPLOYMENT HOUSE OF QUALITY

			Requirements/Capabilities (How's)						
Needs (What's)	*Weights*		**Rapidly deployable sea based platform capable of prolonged operations**	**Stable platform capable of operations in heavy seas**	**Detect and track over the horizon ballistic missile launch and flight path**	**Share real-time sensor, weapon, fire control, and BDA data among coalition forces.**	**Prioritize threats and optimally pair assets with highest probability of kill**	**Designate targets with a low probability of kill to other assets**	
Protect coalition partners from ballistic missile threat	0.27273	0.273	**3**	**1**	**9**	**9**	**9**	**9**	
Operate independent of Nation State territorial boundaries	0.09091	0.091	**9**	**1**	**9**	**0**	**0**	**0**	
Employ over a wide range of environmental conditions	0.13636	0.136	**9**	**9**	**9**	**3**	**3**	**3**	
Assimilate into the Integrated Layered BMD system	0.09091	0.091	**0**	**0**	**9**	**9**	**9**	**9**	
Interoperate with coalition partners	0.13636	0.136	**0**	**0**	**0**	**9**	**9**	**9**	
Destroy TBMS with a high probability of kill	0.27273	0.273	**1**	**9**	**9**	**9**	**9**	**9**	
Check Sum		1.00							
Goal Value									
Threshold Value									
Weighted Performance			3.1	4.0	7.8	7.4	7.4	7.4	37.0
Percent Performance			0.085	0.109	0.210	0.199	0.199	0.199	

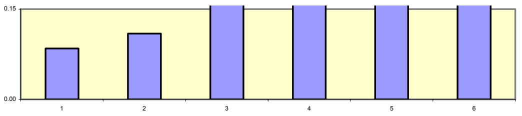

Figure 156. House of Quality 1 Needs to Requirements

MOE's (How's)

Requirements (What's)	*Weights*		Max number of sufficient power supply situations for mission accomplishment per minute	Max number of missions completed regardless of environmental conditions (wind, seas, cloud cover) per minute	Number of days of sustained operations	Probability of detection	Probability of false alarm	Probability of correct identification	Probability of kill	Max number of targets simultaneously tracked and identified per minute	Probability of world wide sensor coverage	Probability of cooperative information exchange (CIX) function operational	Max number of targets effectively engaged per minute	Number of successful BDA's (good or bad) gathered and processed per minute	Number of successful Command and Control decisions made per minute	Max number of designated target files passed to other assets per minute	
			#/min	#/min	days	%	%	%	%	#/min	%	%	#/min	#/min	#/min	#/min	
Rapidly deployable sea based platform capable of prolonged operations	0.085	0.085	**9**	**9**	**9**	**3**	**0**	**0**	**3**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	
Stable platform capable of operations in heavy seas	0.109	0.109	**1**	**9**	**9**	**1**	**0**	**0**	**9**	**0**	**0**	**1**	**9**	**1**	**0**	**1**	
Detect and track over the horizon ballistic missile launch and flight path	0.210	0.210	**9**	**3**	**0**	**9**	**9**	**9**	**9**	**9**	**3**	**3**	**1**	**9**	**3**	**3**	
Share real-time sensor, weapon, fire control, and BDA data among coalition forces.	0.199	0.199	**1**	**0**	**0**	**3**	**3**	**3**	**9**	**9**	**9**	**9**	**3**	**9**	**9**	**9**	
Prioritize threats and optimally pair assets with highest probability of kill	0.199	0.199	**1**	**3**	**0**	**9**	**9**	**9**	**9**	**9**	**1**	**9**	**9**	**9**	**9**	**9**	
Designate targets with a low probability of kill to other assets	0.199	0.199	**1**	**3**	**0**	**9**	**9**	**9**	**9**	**9**	**9**	**9**	**3**	**1**	**9**	**9**	
Check Sum		1.00															
Goal Value																	
Threshold Value																	
Weighted Performance			3.4	3.6	1.7	6.4	6.1	6.1	8.5	7.3	4.4	6.1	4.3	5.8	6.0	6.1	75.6
Percent Performance			0.044	0.047	0.023	0.085	0.080	0.080	0.112	0.096	0.058	0.081	0.056	0.076	0.079	0.081	

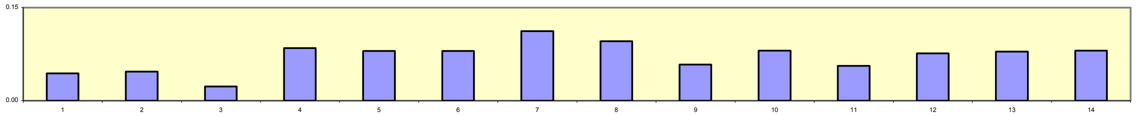

Figure 157. House of Quality 2 Requirements to MOEs

			Functions										
			Receive intel cueing	Acquire non-organic asset information?	Acquire / Detect target	Track target	Identify target	Generate fire control solution(s)	Make C2 / Decision	Engage ballistic missile	Exchange information	Gather and process BDA	
MOE's (What's)	*Weights*												
Max number of sufficient power supply situations for mission accomplishment per minute	0.044	0.044	**1**	**1**	**9**	**9**	**3**	**9**	**3**	**9**	**3**	**9**	
Max number of missions completed regardless of environmental conditions (wind, seas, cloud cover) per minute	0.047	0.047	**1**	**1**	**9**	**9**	**9**	**9**	**9**	**9**	**3**	**1**	
Number of days of sustained operations	0.023	0.023	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
Probability of detection	0.085	0.085	**3**	**3**	**9**	**9**	**3**	**3**	**0**	**3**	**3**	**9**	
Probability of false alarm	0.080	0.080	**1**	**0**	**9**	**0**	**0**	**0**	**1**	**0**	**1**	**0**	
Probability of correct identification	0.080	0.080	**3**	**3**	**9**	**9**	**9**	**1**	**9**	**3**	**3**	**3**	
Max number of targets simultaneously tracked and identified per minute	0.112	0.112	**1**	**3**	**9**	**9**	**9**	**0**	**0**	**0**	**9**	**3**	
Probability of world wide sensor coverage	0.096	0.096	**0**	**9**	**3**	**3**	**3**	**3**	**3**	**3**	**9**	**3**	
Probability of cooperative information exchange (CIX) function operational	0.058	0.058	**0**	**9**	**3**	**3**	**3**	**3**	**9**	**3**	**9**	**3**	
Max number of targets effectively engaged per minute	0.081	0.081	**0**	**3**	**9**	**9**	**9**	**9**	**9**	**9**	**3**	**3**	
Probability of kill	0.056	0.056	**1**	**3**	**9**	**9**	**9**	**9**	**9**	**9**	**1**	**3**	
Number of successful BDA's (good or bad) gathered and processed per minute	0.076	0.076	**0**	**3**	**9**	**3**	**9**	**0**	**1**	**0**	**3**	**9**	
Number of successful Command and Control decisions made per minute	0.079	0.079	**1**	**3**	**9**	**9**	**9**	**9**	**9**	**0**	**9**	**9**	
Max number of designated target files passed to other assets per minute	0.081	0.081	**0**	**9**	**3**	**3**	**3**	**9**	**9**	**0**	**9**	**1**	
Check Sum		1.00											
Goal Value													
Threshold Value													
Weighted Performance			0.9	3.9	7.4	6.2	5.9	4.3	4.9	3.0	5.2	4.1	45.9
Percent Performance			0.020	0.085	0.161	0.135	0.128	0.094	0.107	0.066	0.114	0.090	

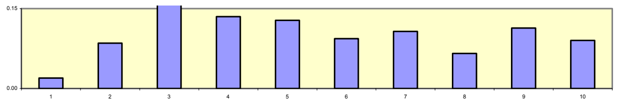

Figure 158. House of Quality 3 MOEs to Functions

			MOP's															
Functions	*Weights*		Number of BM simulated	Number of BM detected	Number of non-detections	Number of false alarms	Number of handoffs	Number of engagements	Number of simultaneous engagements	Number of failed engagements	Mean non-organic detection time	Mean time to relay detection	Mean time to process detection	Mean organic detect time	Mean track formulation time	Mean time to identify	Mean threat prioritization time	Mean weapons pairing time
Receive intel cueing	0.020	0.020	**0**	**3**	**3**	**1**	**0**	**1**	**1**	**1**	**1**	**0**	**1**	**1**	**0**	**1**	**1**	**1**
Acquire non-organic asset information?	0.085	0.085	**1**	**3**	**3**	**1**	**3**	**3**	**3**	**3**	**3**	**9**	**3**	**3**	**3**	**3**	**3**	**3**
Acquire / Detect target	0.161	0.161	**9**	**9**	**9**	**9**	**9**	**9**	**9**	**9**	**0**	**0**	**9**	**9**	**9**	**9**	**9**	**9**
Track target	0.135	0.135	**9**	**9**	**9**	**0**	**9**	**9**	**9**	**9**	**0**	**0**	**0**	**0**	**9**	**9**	**9**	**9**
Identify target	0.128	0.128	**9**	**0**	**0**	**0**	**9**	**9**	**9**	**9**	**0**	**0**	**0**	**0**	**0**	**9**	**9**	**9**
Generate fire control solution(s)	0.094	0.094	**9**	**0**	**0**	**0**	**9**	**9**	**9**	**9**	**0**	**0**	**0**	**0**	**0**	**0**	**9**	**9**
Make C2 / Decision	0.107	0.107	**9**	**0**	**0**	**0**	**9**	**9**	**9**	**9**	**0**	**1**	**0**	**0**	**0**	**3**	**9**	**9**
Engage ballistic missile	0.066	0.066	**9**	**0**	**0**	**0**	**0**	**9**	**9**	**9**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Exchange information	0.114	0.114	**3**	**3**	**3**	**1**	**9**	**3**	**9**	**3**	**3**	**9**	**1**	**1**	**9**	**9**	**9**	**9**
Gather and process BDA	0.090	0.090	**1**	**1**	**1**	**1**	**3**	**9**	**9**	**9**	**1**	**0**	**0**	**0**	**0**	**1**	**1**	**1**
Check Sum		1.00																
Goal Value																		
Threshold Value																		
Weighted Performance			6.7	3.4	3.4	1.8	7.2	7.6	8.3	7.6	0.7	1.9	1.8	1.8	3.9	5.5	7.0	7.0
Percent Performance			0.064	0.033	0.033	0.017	0.068	0.073	0.079	0.073	0.007	0.018	0.018	0.018	0.038	0.053	0.067	0.067

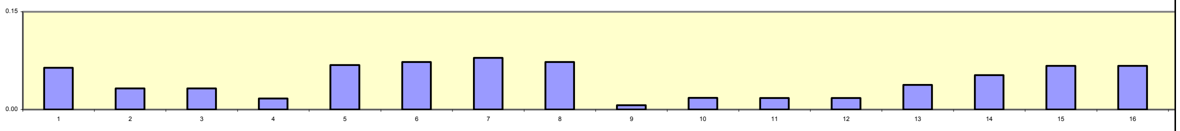

Figure 159. House of Quality 4 Functions to MOPs

APPENDIX B: SYSTEMS ENGINEERING PROCESS

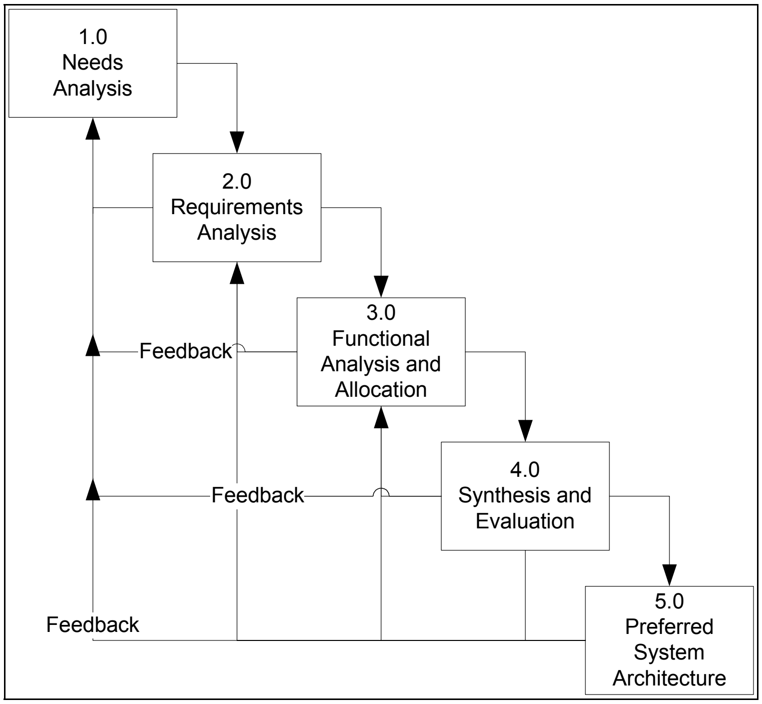

Figure 160. SABR Project Waterfall SE Process

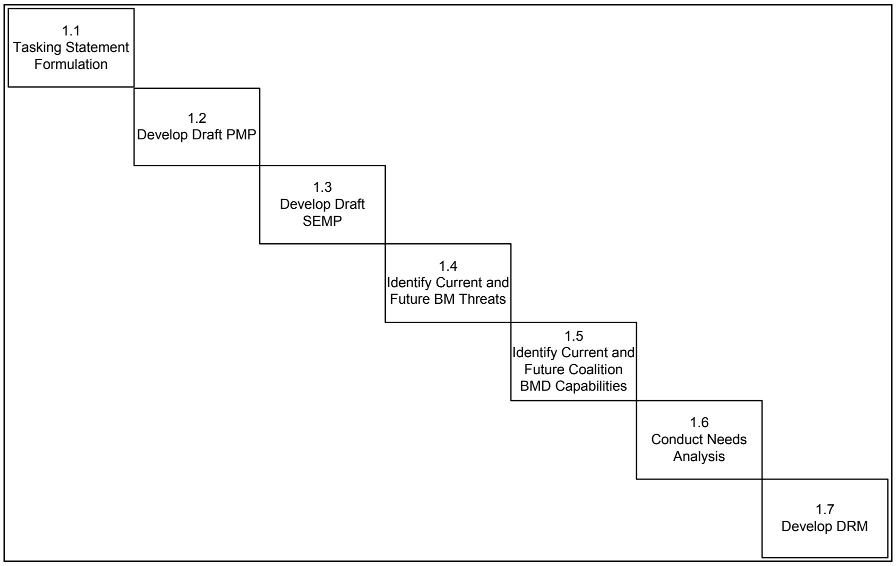

Figure 161. Phase 1 Needs Analysis Detail Waterfall

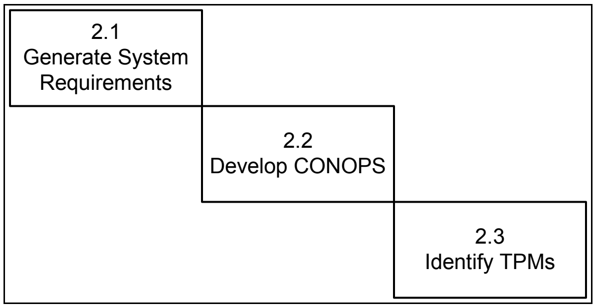

Figure 162. Phase 2 Requirements Analysis Detail Waterfall

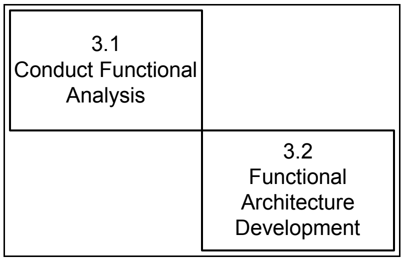

Figure 163. Phase 3 Functional Analysis and Allocation Detail Waterfall

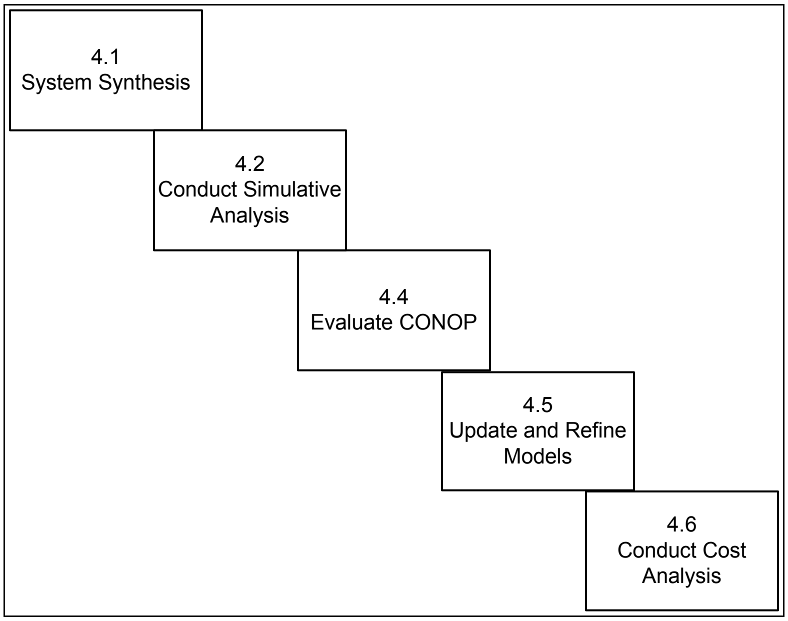

Figure 164. Phase 4 Synthesis and Evaluation Detail Waterfall

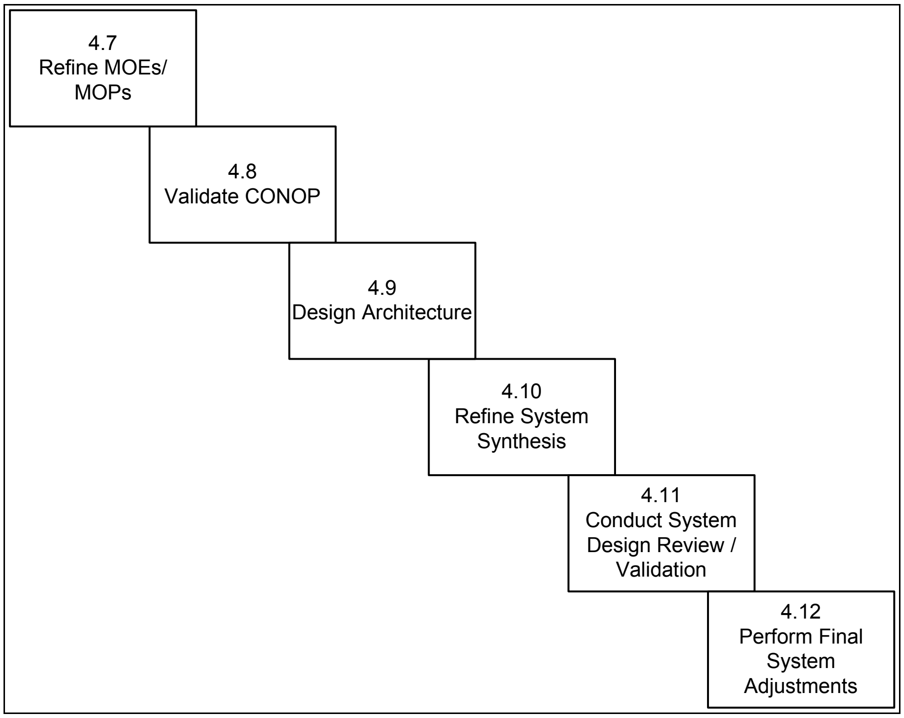

Figure 165. Phase 4 Continued Synthesis and Evaluation Detail Waterfall

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APPENDIX C: AUTOMATED BATTLE MANAGEMENT SYSTEM (ABMS)

A. INTRODUCTION

The Joint Chiefs of Staff define a command and control system as the facilities, equipment, communications, procedures, and personnel essential to a commander for planning, directing, and controlling operations of assigned forces pursuant to the missions assigned.[101] In this sense, the ABMS is the system of facilities, equipment, communications, procedures, and personnel that perform functions in direct support of planning, directing, and controlling operations of forces pursuant to the missions assigned, specifically relating to the high degree of automation at the tactical and operational levels of action. In the definition of the ABMS, the term "forces" is a set of force assets from multiple nation-states, which means that the ABMS is defined to operate across independent nation-states. This section will discuss the requirements and high level design of such a system in detail. Although this report applies concepts to the specific mission of short-range, medium-range, and intermediate-range BMD (SR to IR BMD), the ABMS defined herein is applicable to various mission areas and in situations that involve multiple mission areas.

B. ABMS CONCEPTS

The underlying principle of ABMS as compared to other command and control systems is that the ABMS is by design meant to include and operate across all force assets, including coalition assets. The current command and control systems, such as the Global Command and Control System (GCCS),[102] do operate across service and coalition assets, but not to the degree of the ABMS. Additionally, the ABMS is conceptualized to generate orders such as asset positioning and asset-target pairing. The C2 structure

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[101] JPUB 1-02, p. 101.

[102] GCCS is used by the United States Navy (GCCS-M), United States Army (GCCS-A), British, and Australian assets; additionally, Japanese and South Korean forces are connected to a limited version of GCCS.

supported by the ABMS is envisioned to incorporate automatic generation and execution of orders, but also operate with a man-in-the-loop as designated by the C2.

At first look, the concepts behind the ABMS seem to be at odds with both what is technically feasible as well as what is allowed by doctrine. When viewed in a layered manner, the ABMS is envisioned to operate above the current level of C2 systems and above the individual participating assets, as depicted in Figure 166. This is not to say that the ABMS cannot and will not operate at the unit level, it is merely to say that the ABMS will operate with lower-level systems as opposed to directly controlling unit-level systems. Figure 167 gives an example of current day systems and where they fit into the ABMS architecture as depicted in Figure 166. Work is currently being conducted by the Defense Information Systems Agency (DISA) at the Force/State C2 Level.[103]

Figure 168 shows an architecture design where the ABMS is combined with the Force/State C2. This design is a feasible design, but does not provide a level of autonomy that a nation-state would desire. It is not foreseeable in the near future that a nation-state would give up its inherent right to control and protect its assets over the protection of foreign assets. The separation of the force/state C2 layer and the ABMS accounts for this situation. Additionally, it is likely that there will be procedures (both operational and algorithmic) that a nation-state would not choose to share with any/all participants of the ABMS. The separation of the four-layer model better accommodates the desire of a nation-state to protect its procedures. The separation of the AMBS and force/state layers also places a natural point in which a man-in-the-loop can be injected. This is not to say that the communication between the ABMS and force/state system are done manually. The envisioning of the ABMS does call for an automatic means of communication and execution between the ABMS and force/state system, and in between all layers of the architecture. The above arguments discussing the issues with the three-layer ABMS architecture can also be applied to the two-layer architecture, as well as the one-layer architecture.

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[103] Joint Blue Force Situational Awareness (JBFSA), and Joint Coordinated Real-Time Engagement (JCRE).

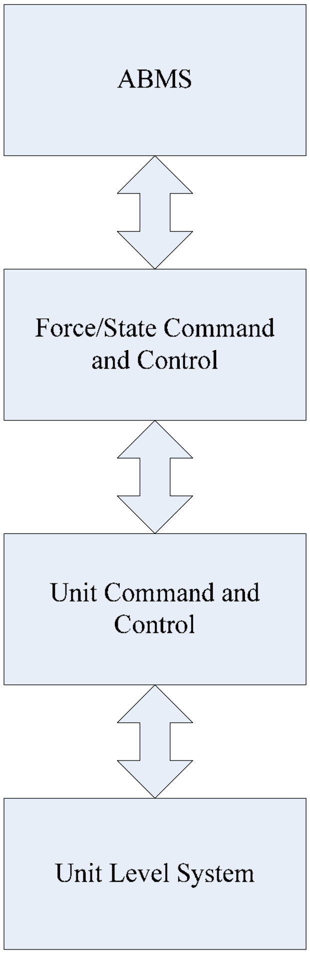

Figure 166. ABMS Architecture Layers

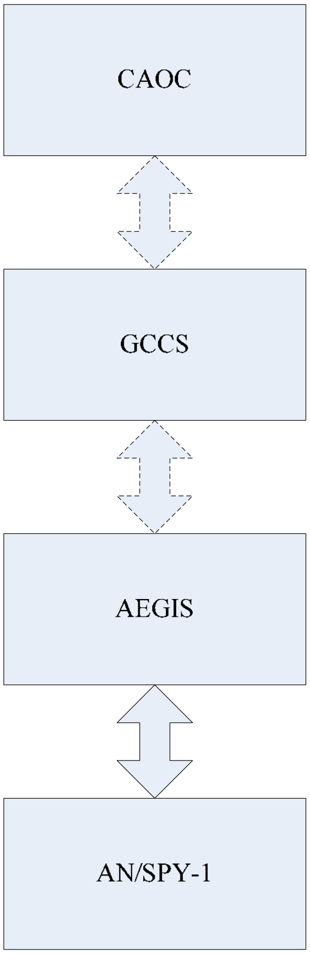

Figure 167. Current Day Example Architecture Layers

Note: The dashed line arrows indicate that data is exchanged between the layers, but C2 information is not. This is not an actual system implementation.

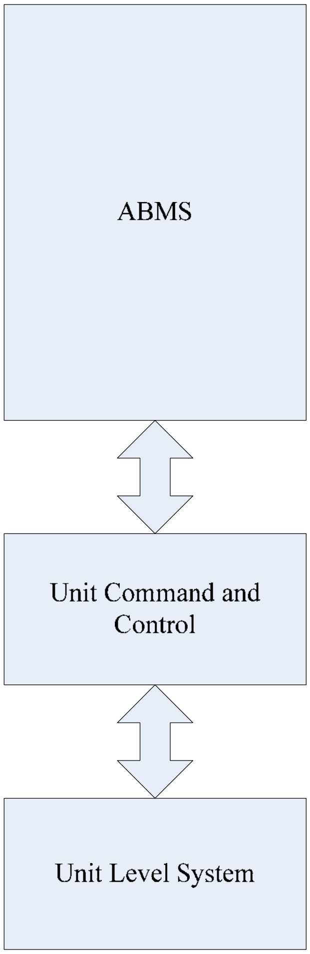

Figure 168. ABMS Combined with Force/State C2

Additionally, the joining of layers reduces the level of abstraction and modularity of the system design. The reduction of layers leads to larger complex layers and ultimately to a monolithic architecture (a single-layer architecture). Given that the envisioned ABMS is expected to be in operation for an extended amount of time it will need maintenance and updating throughout the time it will be used. The added complexity resulting from the merging of layers will lead to increased effort in implementing future modifications and upgrades. Furthermore, it is generally known, regarding information assurance that as the level of complexity of a system increases, the ability to prove overall information security of the system increases. The sensitive nature of the ABMS would require the security of the system to be formally evaluated and proven.

C. SYSTEMS ENGINEERING (SE) PROCESS AND ABMS

The SE process generated needs, requirements, and functions for the overall sea-based SR to IR BMD system. The needs, requirements and functions can be applied to the ABMS. The SE process was applied to a specific problem—SR to IR BMD—the following discussion applies to an ABMS that will operate in a multimission environment. This section will discuss in greater detail the needs, requirements, and functions generated by the SE process and how they apply to the ABMS. The SE process also generated a list of MOEs and a list of MOPs. The items in these lists are used to evaluate the different system architectures that were studied in this project. In that sense, the lists of MOEs and MOPs do not specifically map to tasks that the systems must explicitly perform. When an ABMS is designed with a set of specific facilities, equipment, communications, procedures, and personnel the designers must and will create a specific set of MOEs and MOPs that will be used to evaluate the ABMS.

D. SYSTEMS ENGINEERING (SE) PROCESS NEEDS GENERATED

There are four needs generated through the SE process that can be applied to the ABMS. Each one will be discussed. The system must operate independent of nation-state territorial boundaries; this need applies to the SR to IR BMD system, the BMD system as a whole, and the ABMS. The concept of nation-state territorial boundaries is a political vice physical issue. The ABMS must be approved for use on all assets that are to participate in the ABMS. This is to say that the design of the system and the components that implement the system design must be open among all participating parties and must be agreed on by all initial designing and implementing parties. This leads into the realm of trust between nation-states. There must be a level of trust and agreed on standards between the initial designing and implementing parties in order for the concept of the ABMS to become reality. After design and implementation of the ABMS, future nation-states that want to participate in the ABMS must have the same level of trust among all the already participating nation-states and conform to the set of standards. This need might prove to be the hardest to implement in the real world given the current state of multinational organizations. The degree of effort that is required to come to a consensus in organizations such as NATO and the UN can be extensive for any issue, even issues that most of the participating states are concerned about and generally agree on. That being said, efforts such as the Common Criteria are a step in the right direction.[104]

The system must be employable over a wide range of environmental conditions. Again, this need applies to the system as a whole as well as to the ABMS. This need must be applied to all aspects of the ABMS. The physical housing of the components that comprise the ABMS must be designed in such a way as to protect the components from the operating environment. The ABMS is envisioned to operate on assets that will be deployed on sea, air, land, undersea, and space. Each component must be designed to operate in any of the above environments that the individual component is expected to operate in. A few examples of environmental factors that must be considered are weather (including temperature, humidity, wind, sea state, and precipitation), electromagnetic

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[104] The Common Criteria (CC) is a formalized international set of criteria that are used to evaluate the security of information systems and components. The following countries currently have schemes that support the CC: Australia, Canada, France, Germany, Japan, The Netherlands, New Zealand, Norway, United Kingdom, and United States of America. The following countries do not have a national scheme, but accept the CC: Austria, Czech Republic, Finland, Greece, Hungary, India, Israel, Italy, Singapore, Spain, Sweden, and Turkey.

spectrum, and interference. These factors must be addressed by the design of the component housings as well as by the design of the communication links.

The SR to IR BMD system is designed to fit within the layered ballistic missile defense currently adopted by the United States through the MDA.[105] The ABMS would operate above the layered BMD architecture. The ABMS envisioned would allow the layered BMD system to run within the construct of the ABMS. Furthermore, the ABMS would allow other threat defense systems to run within the ABMS, and run concurrently. In other words, the various threat systems could view the ABMS as a tool in which to operate within.

By the above definition, the ABMS must be able to interoperate with coalition partners. One of the underlying concepts behind the design of the ABMS is that it will operate across all force assets, to include coalition partners. The layered architecture presented in Figure 166 supports the need for the ABMS to interoperate with coalition partners.

One might initially make the argument that the ABMS would need to both protect coalition partners from BM threats and destroy BMs with a high probability of kill. When taking a deep look at the DoD definition of a C2 system and the definition of the ABMS, the execution of the missions that the C2 system plans, directs, and controls is done by commanded assets. The commanded or end asset is responsible for executing the orders, whether that asset is a seaman, soldier, missile, round, or other asset. The ABMS will play a significant part in the ability to protect forces from a BM threat and aid in the end assets ability to execute the commands. Additionally, the ABMS will be a critical player in achieving a high probability of kill for BMs. The actions required to protect forces and destroy BMs are missions that the ABMS can be used to plan, direct, and control; the commands generated by the ABMS will be carried out by layers below the ABMS. The Unit Level System from Figure 166 would be ultimately responsible for the destruction of BMs with a high probability of kill.

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[105] MDA Life.

E. SYSTEMS ENGINEERING (SE) PROCESS REQUIREMENTS GENERATED

The SE process also generated a list of requirements that the SR to IR BMD system must meet. As above, the application of the generated requirements will be discussed in relation to the ABMS. The first requirement pertains to the ability of the system to be rapidly deployed and capable of prolonged operations. The specific requirement generated pertains specifically to the sea-based platform; however, this applies to the ABMS as well. Any asset that houses equipment that is a part of the ABMS will have an associated logistics support requirement. Components that fit within the ABMS must be designed with logistics support in mind during the design phase. Specifically, significant effort should be put into insuring that the designed components have the lowest amount of logistics support requirements as feasibly and economically possible. Additionally, the reliability and maintainability of the components that comprise the ABMS must also be considered. This requirement includes applying the concepts of integrated logistics support throughout the life cycle of the system.[106]

The overall system including the ABMS must be a stable platform capable of operations in heavy seas. This requirement states that the system must operate over a wide range of environmental conditions. This requirement goes further and states that the system must operate in heavy seas. This study has used a sea state of 6 on the Beaufort scale as the definition of heavy seas in which the system must be capable of operating in.[107] The components of the ABMS used on the sea-based platform must be capable of operating in such conditions if the sea-based platform is to perform missions in such conditions. The components of the ABMS must be designed to withstand, at a minimum, the maximum sea state that the sea-based platform will be expected to experience. The

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[106] The concepts of Integrated Logistics Support include: Maintenance and Supply Plan, Supply Support, Support and Test Equipment, Facilities, Manpower/Contractor Technical Services, Training and Training Equipment, Technical Documentation, Computer Resources, and Packaging, Handling, Storage, and Transportation.

[107] The Beaufort scale defines a sea state of 6 as having waves with a height of three meters. Simulations will need to be done on the sea-based platform to estimate the likely pitch, roll, and yaw that the platform will experience in expected sea states.

amount of time that the sea-based platform is expected to experience the maximum designed sea state, as well as the rate of occurrence of such a sea state, must also be considered when designing the components of the ABMS.

The sharing of sensor, weapon, fire control, and BDA data among participating forces in near real-time is central to the ABMS having the ability to perform as defined at the beginning of this section. The above categorizations of data are among the data that is critical to the ABMS being able to provide services to the commander. The envisioned ABMS would perform the sharing of this data, other data, as well as other C2 requirements.

One example of another C2 function that the ABMS would perform is the passing off of targets that an asset reports as having a low probability of kill. The layers below the ABMS, specifically the Unit Command and Control Level, would be the best able to determine the probability of kill that the unit's assets can achieve. This determination would be passed up the layers to the ABMS. The ABMS would take such determinations from all participating units and compute the course of actions that would best address the threat scenario. The other aspect of computing the course of actions that best address the threat situation is to prioritize the targets that compose the threat scenario. Again, the ABMS would use the information provided via participating units to prioritize the targets and optimally pair assets to targets in a manner that best addresses the threat scenario.

The actual detection and tracking of targets would occur at the unit-level layers. A radar system such as the AN/SPY-1 would perform the initial detection and tracking of contacts. This data would most certainly be consolidated and be passed up to the ABMS through the layers of ABMS architecture. The ABMS could be used to merge contact information among various assets and end detection systems to better identify the target, such as correlating radar track information from one asset with infrared sensor track information from another asset.

F. SYSTEMS ENGINEERING (SE) PROCESS FUNCTIONS GENERATED

The requirements generated by the SE process lead to functions that the system must perform. As seen with the needs and requirements generated by the process some apply to the ABMS, while others will fall to layers below the ABMS. The first function generated does apply to the ABMS. The ABMS must be able to receive intelligence cueing. In fact, it is envisioned that the intelligence assets will be seen as participants or assets just as a sea-based platform would be. The ABMS would use this intelligence cueing information in the calculations to determine the best course of actions. For instance, the ABMS could take intelligence on where threats are known or suspected to be located and generate commands to optimally place the assets to counter the threat scenario.[108]

The ABMS correlates track information from various participants to better identify a target. The ABMS would not perform this function only at the beginning phase of tracking a contact, but continue it throughout. If the target was deemed a threat and action was to be taken against the threat, the ABMS would again correlate the track information of end detection assets in order to determine a more comprehensive BDA. The ABMS would then determine the best course of actions to further deal with the threat if the BDA determined that the threat had not been eliminated.

The ability of the ABMS to pass information among participants goes beyond the concept of having a COP across the participants. Current day COP systems share track information among assets giving all participants position and track information on contacts held by any participant. They also correlate discrepancies in track information among the participants and present the best track information to participants. The ABMS is envisioned to pass this information as well as more detailed information about the participating assets. In order for the ABMS to perform the functions envisioned, the participating units will have to provide more detailed information than is currently provided in today's COP systems. Specifically participating assets would need to provide system status information to the ABMS, as well as weapon employment capabilities. Participating assets need not provide the exact number of weapons or the specific capabilities of such weapons to the ABMS, but would need to provide sufficient information to the ABMS in order for the ABMS to perform the function of optimally addressing the threat scenario based on the capabilities of participating assets.

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[108] Brown discusses a model that optimizes defender asset placing based on attacker asset placing.

As mentioned above, there are functions that would be performed at layers below the ABMS. The detection and tracking of targets would occur at the unit level layers of the architecture. The generation of fire control solutions will also occur at the unit levels of the architecture. The ABMS will, as mentioned, optimally pair available assets to targets in an effort to best address the threat scenario. The execution of the actions necessary to engage a target will be carried out by layers below the ABMS, specifically the unit-level layers.

G. INFORMATION ASSURANCE (IA) AND ABMS

DoD Directive 8500.1 (DoDD 8500.1) Information Assurance applies to all DoD-owned or -controlled information systems that receive, process, store, display, or transmit DoD information, regardless of mission assurance category, classification or sensitivity.[109] The ABMS, as is any C2 system, is a system that deals with and depends on information and the interconnection between participating assets. The ability to gather, produce, and disseminate information securely is at the very heart of any C2 system. Furthermore, DoDD 8500.1 states that an information system (IS) shall maintain appropriate levels of confidentiality, integrity, authentication, nonrepudiation, and availability; the five components of Information Assurance (IA). As such, one cannot fully discuss the issues regarding the design of a C2 system without discussing IA-related issues. Additionally, the five components of Information Systems Security (INFOSEC): personnel security, physical security, communications security (COMSEC), computer security (COMPSEC), and emissions security (EMSEC) will be discussed in this section.

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[109] DoDD 8500.1, 2.1.2, p. 2.

H. COMPONENTS OF INFORMATION ASSURANCE (IA)

The availability of the data and information that the ABMS uses and produces is vital to its ability to perform the functions required of it. Availability is defined as timely, reliable access to data and information services for authorized users.[110] The design of the ABMS must insure the availability of data and information across participating assets. The storage and communication of data and information both play a role in availability. The large distances and range of environments that will separate participating assets of the ABMS requires a robust communications network. The communications architecture should not be a designed component of the ABMS. The communications architecture should be separate from the ABMS; in other words, the ABMS would be a user of the communications network. The separation of the ABMS and communications network will result in numerous benefits. This will allow for maintenance and upgrades to the ABMS and the underlying communications network components to occur independent on each other. Resulting in each component to be designed to best handle the functions it performs. A valid candidate for an architectural design of the communications network is depicted in Figure 169, a representation of the current day TCP/IP stack, or model of communications that occur across the Internet.[111] This is not to say that the ABMS will or should be run across the Internet. In this model, the ABMS would sit at the Application layer as depicted in Figure 170. The architectural design presented in Figure 169 allows for the use of both wired and wireless communications. Additionally, as shown with the success of the Internet and its predecessor ARPANet, such an architectural design allows for a robust communications network that is flexible and able to continue operations under high stress environments. The storage of data and information must also been considered in order to insure their availability. The reliability and hardening capabilities of solid state storage lends products based on such technology to be viable candidates worthy of design consideration across all components of the ABMS.

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[110] CNSSI 4009, p. 5.

[111] Kurose, p. 48.

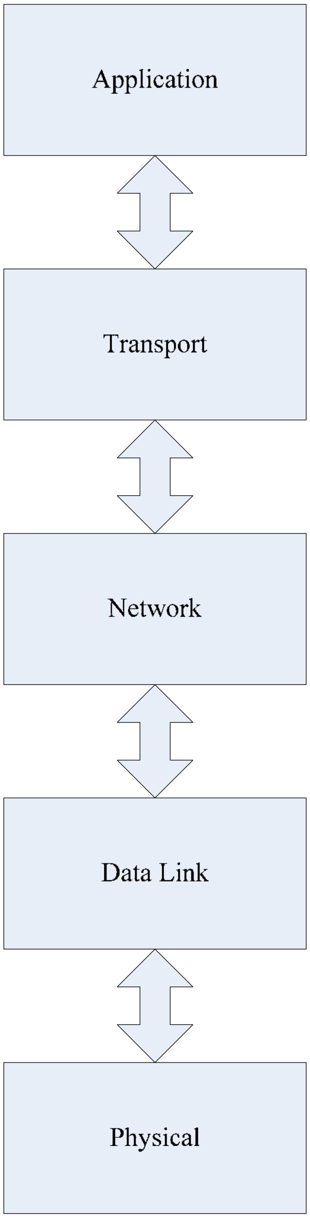

Figure 169. TCP/IP Stack [KURO]

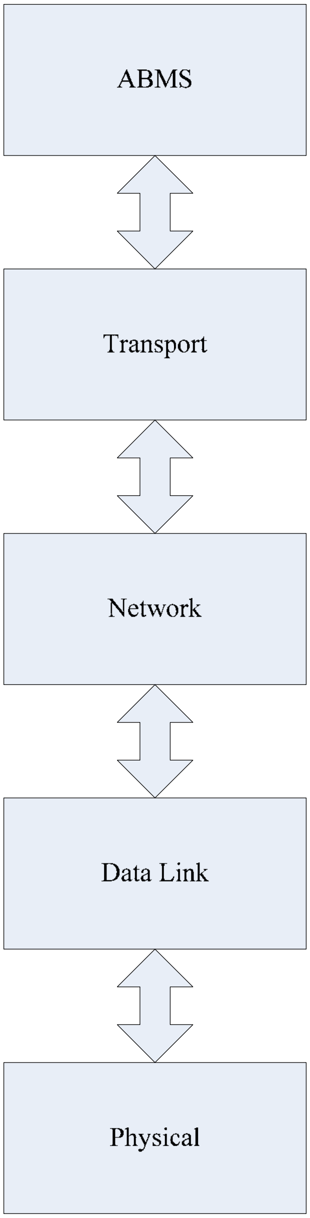

Figure 170. ABMS as Application

The large amounts of data and information that the ABMS will need to handle and the way in which that data and information will be processed by large land based installations leads to RAID architectures to be considered for storage needs. Redundant Arrays of Independent Disks (RAID) is a multidisk architecture that is used to address data availability and reliability in the occurrence of disk failures. There are a variety of open and proprietary RAID standards that should be evaluated for system performance as a part of ABMS components. The current trend in processor design has shifted from doubling processor speed approximately every 18 months to increasing the number of processors that are on a single chip. The continued increase in the number of processors per chip leads to the viable need to evaluate chip and motherboard memory architectures implemented as RAID architectures.

The integrity of the data both as it is stored and during transfer must also be addressed. CNSSI 4009 defines integrity as the quality of an IS reflecting the logical correctness and reliability of the operating system; the logical completeness of the hardware and software implementing the protection mechanisms; and the consistency of the data structures and occurrence of the stored data. The logical correctness and completeness requirements from the definition are achieved through formal methods analysis. Due to the sensitive nature of the data and information that is handled by the ABMS and the range of nation-states that will contribute to the ABMS a formal security model, as depicted in Figure 171, vice an informal security model, shown in Figure 172, must be used to satisfy the completeness and correctness requirements imposed on the ABMS. The formal methods analysis will also verify the consistency of the data structures used by the ABMS. The formal methods analysis process must be open to and approved by all participants. This is required for all participants to have trust in the ABMS and its implementation. To address the issue of stored and transmitted data consistency integrity check values should be used.[112] Integrity check values that provide both a means to detect and correct modifications should be employed, especially across communication links.

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[112] An integrity check value is a checksum capable of detecting modification of an IS [CNSSI 4009].

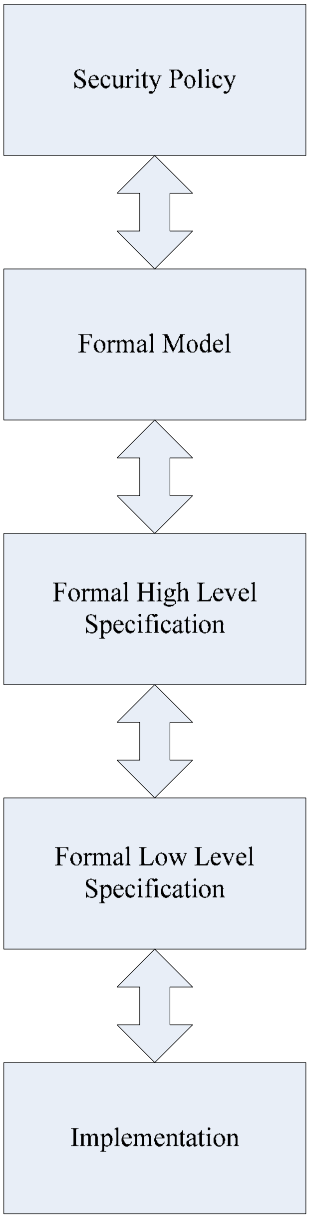

Figure 171. Formal Security Model [CS3600]

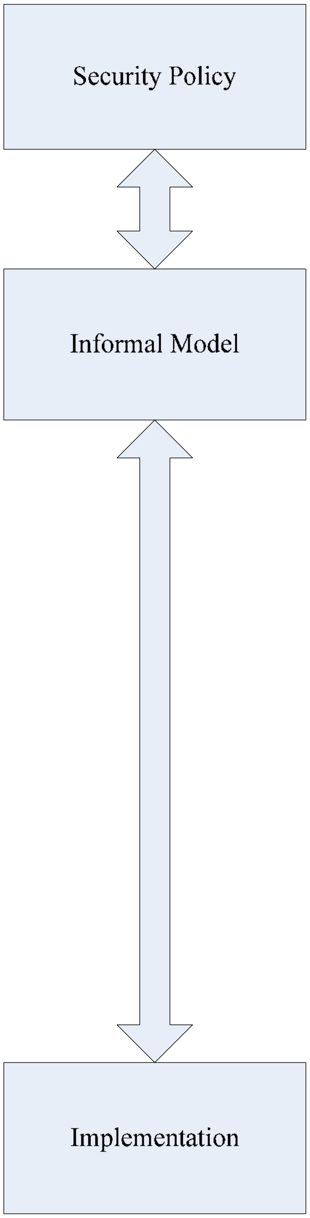

Figure 172. Informal Security Model [CS3600]

By using integrity check values that can detect and correct modifications the system will be able to recover from unauthorized or unintentional modifications. At a minimum, integrity check values that can detect modifications must be used by the system.

Generally, it is understood that confidentiality of information applies to people, however, confidentiality of information extends to processes and devices as well. The CNSSI 4009 defines confidentiality as the assurance that information is not disclosed to unauthorized individuals, processes, or devices. Across communications links and on storage devices, encryption methods can and need to be used to address the confidentiality of the information. This, however, is not sufficient to address all the confidentiality concerns that are associated with the ABMS. The access mechanisms that are provided by both the operating systems and hardware that comprise the ABMS components must be designed in a way to control access to information that the ABMS handles. There is current work being done in trusted computing environments and multilevel security environments.[113]

The use of the term unauthorized in the definition of confidentiality implies that there are authorized individuals, processes, and devices that are allowed access to the information. An individual, process, or device is authorized through the act of authentication. The definition of authenticate from CNSSI 4009 addresses the issue of verifying the identity of entities that interact with an IS. There are three ways in which the identity of a person can be verified. The first way is through the use of passwords, or other information that the individual knows. The use of tokens, such as the Common Access Card (CAC), is representative of validating a user's identity through their control of a unique item, or something that the individual has. The third way that an individual's identity can be verified is by validating their biometrics, such as fingerprints or retinal scans; biometric information is an example of something that the individual is. The same concepts applied to verifying the identity of individuals can be applied to the components of the ABMS. The concept of something that is known is easily transferred

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[113] The Trusted Computing Exemplar (TCX) is a project intended to make high assurance development methods and technology available to the DoD and U.S. Government. The Monterey Security Architecture (MYSEA) is intended to develop high assurance security services and integrated operating system mechanisms to protect distributed, multilevel, heterogeneous, computing environments from malicious code and other attacks. Both projects are areas of research at the Cebrowski Institute for Information Innovation and Superiority at NPS.

to computer systems through the use of shared secrets between the communicating processes. The use and validation of digital signatures also authenticate identity through knowing information. The concept of authenticating a component by an item it possesses can be implemented through the use of hardware dongles. The use of hashing techniques on the code of a module can be thought of as a fingerprint of sorts for the module, or something that the module is. Due to the sensitivity of the ABMS, at a minimum strong, or two-factor, authentication will need to be used; some aspects of the ABMS will need to employ a three-factor authentication scheme.

There are two aspects of nonrepudiation, as defined by CNSSI 4009: the first is that the sender of data is provided proof that the data was received; the second is that the receiver is provided proof of the sender's identity. As with confidentiality, the concept of nonrepudiation depends on the authentication of entities. Providing the sender with proof that the receiver did receive the data can be a nontrivial issue, especially in the context of C2 applications. A simple assurance that the receiver correctly received the data is not sufficient in a C2 application. The sender must be provided additional information, such as whether the receiver understood the data and whether or not the receiver is or will act according to the data. For instance, it is not sufficient for an order to act to be given to an asset, and the only information that is returned to the sender (command entity) is that the receiver (subordinate entity) correctly received the command. In this case, the command entity would want to know whether the subordinate understood the order; whether the subordinate is able to comply with the order; and be able to receive routine updates on the status of executing the order. Being a C2 system, the ABMS must provide nonrepudiation of this nature. The second aspect of nonrepudiation is implemented today via the use of digital signatures.

I. COMPONENTS OF INFORMATION SYSTEMS (IS) SECURITY

CNSSI 4009 defines INFOSEC as the protection of information systems against unauthorized access to or modification of information, whether in storage, processing or transit, and against the denial of service to authorized users, including those measures necessary to detect, document, and counter such threats. There are five components that comprise INFOSEC: personnel security, physical security, COMSEC, COMPSEC, and

EMSEC. All five components of INFOSEC must be addressed in the design of the ABMS and its components. Additionally, the techniques, tactics, and procedures that address and enforce INFOSEC for the ABMS must be approved and adhered to by all participating nations and assets. The underlying principle of defense-in-depth that is associated with other forms of security is also applicable to INFOSEC; the ABMS must incorporate a defense-in-depth security architecture to include INFOSEC.

Personnel security involves the trustworthiness and suitability of individuals to perform in position of trust. In DoD, the trustworthiness and suitability of an individual is ascertained through the conduct of a personnel security investigation (PSI).[114] The trustworthiness required by individuals that will access the ABMS is intended to be determined by an already established PSI. This is to say that an individual already determined to be trustworthy at the levels required for use of the ABMS will not need to go through a separate PSI specific to the ABMS. Additionally, the PSI conducted is not envisioned to be conducted by members from all participating nations; rather, participating nations would honor investigations conducted by other participating nations in context to allowing access and use of the ABMS. The concept of honoring other nations' assessments is consistent with the ideas and implementation of the Common Criteria. The criteria by which personnel are judged for their trustworthiness must be agreed on and consistent across all participating nations. The issue of initial personnel whose trustworthiness is based on investigations that do not meet the agreed on criteria must be addressed during the design phase of the ABMS. There must also be procedures for incorporating personnel from nations who begin to participate in the ABMS after the date the ABMS is brought online.

Physical security has perhaps been the oldest and most well-known form of security. The concept of defense-in-depth often began with physical security concepts. JPUB 1-02 defines physical security as that part of security concerned with physical measures designed to safeguard personnel; to prevent unauthorized access to equipment installations, material, and documents; and to safeguard them against espionage, sabotage, damage, and theft. Physical security begins with controlling the access to the installation as whole; the installation being viewed as the base or port. The next

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[114] JPUB 1-02, p. 409.

significant layer of security would be the control of access to the building or ship. In applications that handle highly sensitive data, access to the rooms that house equipment that handle the highly sensitive data is also controlled. The last steps in physical security occur at the actual component level. The physical construction of components can also been done with security in mind. Mechanisms can be put in place such that if the external housing of a component is penetrated in an unauthorized way, then the data and internal components are destroyed and security ensured. The physical security associated with the ABMS and its components must include these defense-in-depth concepts. When an actual ABMS is designed, it will likely be the case that the physical security of the installation, building/ship, and room will be enforced through policies and procedures that are common across a range of sensitive applications. The design of the physical security required in the definition of the ABMS is not envisioned to require the complete overhaul of the physical security of the installations, buildings, and even rooms in which the ABMS or its components are located; this is to say, the design of the ABMS will assume that the physical security measures external to the ABMS components are already in place.

COMSEC is already an integral part of present-day C2 systems, and will continue to be. COMSEC includes measures and controls taken to deny unauthorized individuals information derived from telecommunications and to ensure the authenticity of such telecommunications. COMSEC includes: cryptosecurity, transmission security, emissions security, and physical security of COMSEC material.[115] The most well-known form of COMSEC is the use of cryptography between communications links. Cryptography is used between wired and wireless links, and is even used internal to systems in highly sensitive applications. The other hand that goes along with the use of cryptography is the security of the cryptographic keys or the security of COMSEC material. The need to securely store and control access to cryptographic material has been known since the time cryptographic codes were first used. The need to securely transmit the keys between participants has also been an issue of great concern. With the inception of digital communications and the use of cryptography between participants who are physically separated by large distances and who might not ever physically meet,

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[115] CNSSI 4009, p. 11.

the need to securely transmit cryptographic keys across untrusted communications lines arose. In the early through middle part of the last century, this was still a problem. With the advent of public-key cryptography, or asymmetric cryptography,[116] the secure transmission of cryptographic keys across untrusted communications lines became possible. Due to the nature of the participants of the ABMS, a comprehensive public-key cryptographic system will need to be incorporated into the design. In present-day, public-key cryptography, the use of public keys is limited to the encryption of small pieces of information, such as symmetric keys,[117] due to the complexity associated with encrypting and decrypting data using asymmetric cryptography. The use of public-key cryptography could be used at the component level of the ABMS to securely transmit session keys between the communicating components. The transmitted session key would be a symmetric key that is only known between the two communicating links and only used for the duration of the communication.

CNSSI 4009 defines COMPSEC as measures and controls that ensure confidentiality, integrity, and availability of IS assets including hardware, software, firmware, and information being processed, stored, and communicated. In practice, COMPSEC is achieved through clear and consistent policies that are able to be implemented and enforced by the systems. For example, the ABMS would need to have clearly defined account management policies and resource accessing policies among others. An account management policy includes business rules regarding account passwords, account lockout schemes, and account creation and deletion schemes. After a policy is determined, a set of guidelines should be drafted. The guidelines would describe methods that can be employed to satisfy the policy requirements. At the lowest level, there would be techniques and procedures that are used to implement the policy based on the guidelines. For example, the account management policy would include procedures for creating and deleting accounts. Each policy would also need to include procedures that address event logging and the auditing of the created logs. The nature of

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[116] Asymmetric cryptography uses two separate but mathematically related keys to encrypt and decrypt data. Each participant has their own unique pair of keys, one public-key that everyone knows, and a private key that the participant keeps secret.

[117] Symmetric cryptography uses a single key to encrypt and decrypt data; the single key must be known by all participants.

the ABMS leads to the adoption of a Mandatory Access Control (MAC) policy vice a Discretionary Access Control (DAC) policy in reference to accessing resources. A MAC policy is one in which the user is given limited or no control over allowing other users to access resources that they own. A DAC, on the other hand, allows the users to have full control over the resources under their ownership and just as easily allows other users to gain access to those resources. It is standard practice in sensitive applications to employ MAC policies over DAC policies. A DAC policy is generally less secure and has the tendency to allow for the leaking of information. A MAC policy has a greater ability to protect the system from unintentional information leaks. The policies of the ABMS would also clearly state the specific roles and responsibilities of the personnel who use and manage the ABMS.

EMSEC has been a topic of interest in both the theoretical and real worlds since well into last century. The ability to determine information emanating from and through electronic equipment has been demonstrated numerous times through the detection of the emitted electromagnetic field.[118] There are also recognized methods to address the vulnerabilities associated with EMSEC. A common method used to address EMSEC is through electromagnetic hardening components, which can be done through the use of Faraday cages. Faraday cages are designed to prevent the emanations of electromagnetic fields, thus reducing the ability to detect electromagnetic fields emanating from the area internal to the cage. The ABMS needs to be designed with Faraday cages at the component level, both to prevent external detection of internal electromagnetic fields and electromagnetic interference (EMI). Due to the nature of ABMS, the use of fiber optic cabling is preferred over the use of metal cabling, such as copper. Fiber optic cables have a significant advantage over metal cables in that fiber optic cables do not emanate electromagnetic fields external to the cable itself. The detection of signals transmitted across fiber optic cables is possible, but is more difficult to do than the detection of signals transmitted across metal cables. If metal cabling is required to be used between components of the ABMS, shielded metal cabling must be used. The concept of shielded

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[118] There are proven methods to retrieve signals as they travel through copper wire without the need of physically penetrating the cabling. There are methods to reproduce screen images of CRT monitors.

cabling is similar to a Faraday cage, in that the shielding is designed to limit the electromagnetic emanations of the cable, while also limiting EMI.

J. FUTURE WORK

The next step in the ABMS design process is to expand on the ideas and begin to come up with an actual ABMS system design. The ABMS is a component system of the BMD system that can be designed and implemented independent of the BMD system. This is to say that the progress of the ABMS does not need to be held up by the progress of the BMD system. The design of the ABMS would definitely fall under the cognizance of the DoD Information Technology Security Certification and Accreditation Process (DITSCAP);[119] additionally, the ABMS would also be viewed as a national security system as defined in the CNSSI 4009. As such, the appropriate directives and instructions would need to be thoroughly reviewed and adhered to throughout the lifecycle of the ABMS. The DITSCAP is a current, applicable directive that would guide the design efforts of the ABMS. During the design phase of the ABMS, an analysis would need to be done to determine the best design among a list of candidate solutions. This analysis would need to include results from models and simulations of not only the ABMS by itself, but how the ABMS interacts with other systems. NETWARS is an example of an application that could be used to model the interaction of the ABMS with the underlying communications network. Before the design of the ABMS can begin, the partner nations would need to come to an agreement that the level of coordination and cooperation afforded through the implementation of the ABMS is something that all parties want and will fully participate in. Without this agreement, the ABMS as envisioned for the BMD system will not become a reality.

K. AUTOMATED BATTLE MANAGEMENT SYSTEM (ABMS) SUMMARY

The ABMS, as required by this SABR project, is a realistic and attainable system. Specific needs, requirements, and functions generated by the SE process for the SABR

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[119] The DITSCAP applies to the acquisition, operation, and sustainment of any DoD system that collects, stores, transmits, or processes unclassified or classified information [DoDI 5200.40].

system were mapped to the ABMS itself and to the layers within the ABMS architecture. Concepts that must be applied during the design of the ABMS were presented; specifically, the five components of IA (confidentiality, integrity, authentication, nonrepudiation, and availability) and IS (personnel security, physical security, COMSEC, COMPSEC, and EMSEC). The next step in the lifecycle of the ABMS is for an initial group of nation-states to come to an agreement on the need for and desire to design the ABMS. Once an agreement has been reached, an open and formal design of the ABMS can begin, ultimately leading to the implementation of a coalition-wide, automated C2 system.

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